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A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches

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ABSTRACT

The energy delivery of a solar-energy system is generally associated with the sun's available irradiance and spectral content, as well as a variety of environmental and climatic factors and inherent system and component performances. However, other external factors relating to geographical location and conditions can have even greater impacts on system performance. Among these, soiling is a commonly overlooked or underestimated issue that can be a showstopper for the viability of a solar installation. This paper provides a comprehensive overview of soiling problems, primarily those associated with "dust" (sand) and combined dust–moisture conditions that are inherent to many of the most solar-rich geographic locations worldwide. We review and evaluate key contributions to the understanding, performance effects, and mitigation of these problems. These contributions span a technical history of almost seven decades. We also present an inclusive literature survey/assessment. The focus is on both transmissive surfaces (e.g., those used for flat-plate photovoltaics or for concentrating lenses) and reflective surfaces (e.g., mirrors or heliostats for concentrating power systems).

Contents

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1. Introduction

Renewable energy technologies are a focus for meeting current concerns regarding energy security, the environment, and global climate change in developed and developing nations. Among these clean-energy approaches, solar technologies continue to grow in residential, commercial, agricultural, and industrial applications. For electricity generation, photovoltaic (PV) and concentrating solar–thermal power (CSP) systems are the main technologies used to convert the sun's abundant radiation. Design of these solar-energy systems encompasses wide-ranging material science and engineering, as well as innovative approaches to maximize system performance and lower cost. For both PV and CSP, the sun's electromagnetic radiation must interface (via transmission or reflection) with an intermediate surface before the energy can be transformed into useful energy. For PV modules, this intermediate surface is typically a glass or polymer module cover or concentrating lens; for CSP, highly reflective mirrors redirect light onto a central focal point. Research has been directed primarily to improve the components of the system. Fig. 1 shows one indication of the success of this research investment—the improvement of solar-cell conversion efficiencies over time. These improvements, some of which are only fractions of a percent from device to device, have been foundational in lowering the costs of the PV system through better area utilization and balance-of-systems investments.

A substantial amount of time and money have been invested to bring solar-system performance to its current credible position and to ensure reasonable system and component reliability (e.g., encapsulations commensurate with 30-year lifetimes, developing qualification tests and accelerated-lifetime testing procedures). However, far less time and money have been invested in addressing externalities that can be showstoppers for technology deployment. One such externality not generally considered in deploying and operating most solar systems is the impact of sedimentation (i.e., dust or dirt particles) on intermediate or exposed surfaces. Dust inherently disrupts the intended function

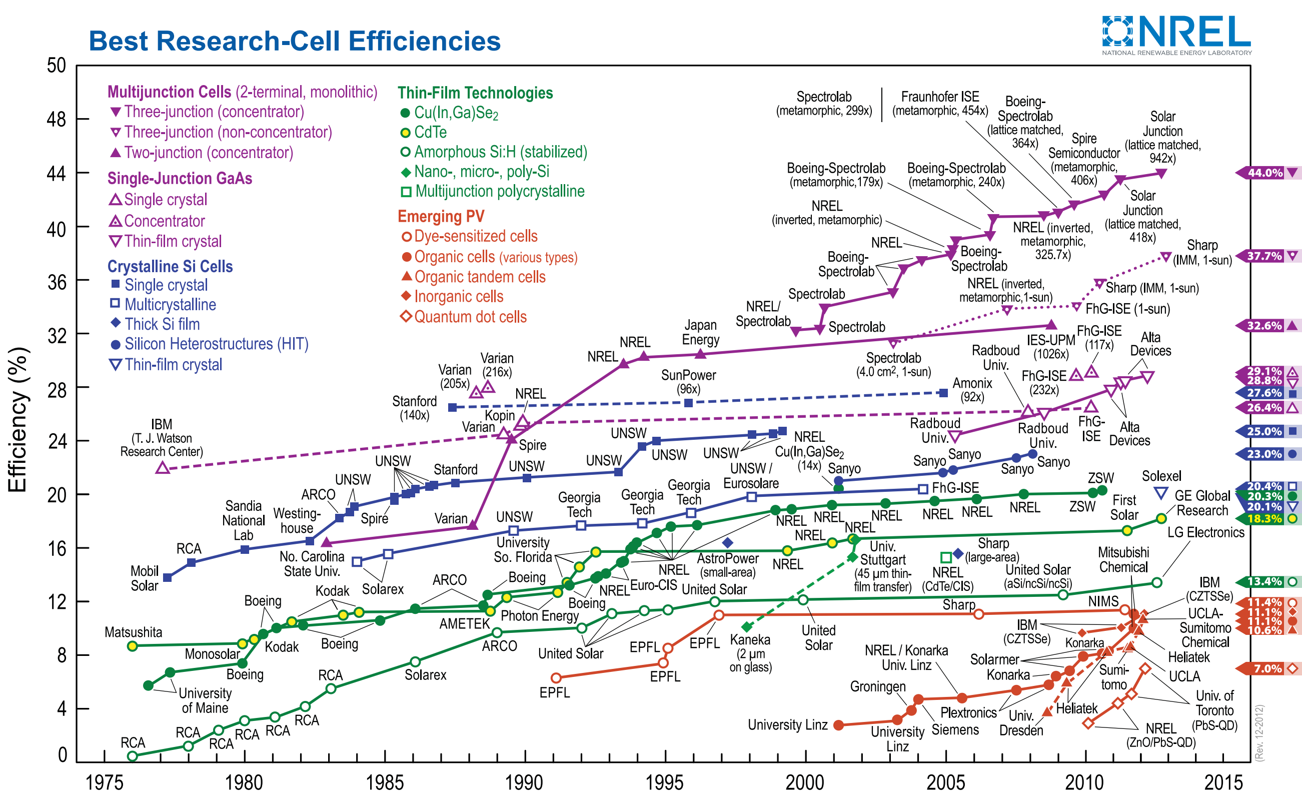


Fig. 1. Research solar cell efficiencies for various technologies measured under standard conditions. This chart has been maintained by L.L. Kazmerski at the National Renewable Energy Laboratory since 1984. Because progress continues at a rapid pace, this figure represents a snapshot of the status in March 2013. The reader is referred to www.nrel.gov and http://en.wikipedia.org/wiki/Solar_cell for the latest version.

at that first surface/light interface, which can significantly reduce (by far more than just fractions of a percent) the power output and efficiency or can completely terminate system operation. Only recently has the issue of dust come to the forefront because of increased interest and deployment in those parts of the world where such soiling is a considerable problem—and coincidently, where solar energy use makes much sense. Although many studies throughout the world are discussed in this review, we focus somewhat greater emphasis on sand and dust issues in the desert climates.

Dust is a general term for any particulate matter less than 500 μm in diameter, which is about the dimension of an optical fiber used for communications or 10-times the diameter of a human hair. Dust can comprise small amounts of pollen (vegetation, fungi, bacteria), human/animal cells, hair, carpet and textile fibers (sometimes termed microfibers), and, most commonly, organic minerals from geomorphic fallout such as sand, clay, or eroded limestone [3]. Atmospheric dust (aerosols) is attributed to various sources, such as soil elements lifted by the wind (aeolian dust) [70,71,99–102,215,219,220], volcanic eruptions, vehicle movement, and pollution. The particle size, constituents, and shape of the dust vary from region to region throughout the world. Furthermore, the deposition behavior and accumulation rates can vary dramatically in different localities. These factors are based on the geography, climate, and urbanization of a region. Important dust characteristics are typically size and distribution, density, shape, composition and chemistry, and charge. Important ambient conditions that relate to these characteristics are humidity/moisture, gradients, wind velocity (variation in direction, speed), and time variations.

Research has been conducted and observations made on this subject for more than seven decades. However, the fundamental properties of dust and its effect on energy transfer are still not fully understood—nor is there a clear solution to the problem. Today, the most effective mitigation technique is physically washing the surfaces of the solar devices with water or detergent solutions. This technique is labor and resource (water) intensive, which, in turn, can lead to high operation and maintenance costs. Furthermore, in the regions where solar availability is most abundant, water resources are typically scarce, thus making wet cleaning an unfavorable mitigation approach.

The purpose of this paper is to provide a comprehensive review of previous and current research and activities. We also want to provide insights to be able to predict the effect (reduction) in the power output of a solar system based on the dust accumulation mechanics, chemistry, and optics. There are also relationships to the technology employed (the hardware), the geographical location, and the environmental conditions. Related to this are discussions of the relationships between the ambient or airborne dust characteristics and the dust that finally accumulates on the collector surfaces. We highlight key studies, relationships, observations, and mitigation techniques, and evaluate and offer some other approaches for mitigation and future research. Several other reviews have been published, including excellent recent papers by Mani and Pillai [184] and Mekhilef et al. [219], which assess the status of research dealing with dust impact on PV system performance and present a framework to understand the underlying factors for dust settling and mitigation. The Mani and Pillai contribution contains a useful and important categorization of climatic zones, the conditions in those zones that influence PV performance, and recommendations for mitigation of dust issues. They also elucidated the critical relationship between the transmission of the incident light and the particle sizes, compositions, and the loading (deposition density, particle morphology, size and distribution, and the relationship of the surface to the incident dust flow). Our review builds on such foundational work by covering the following: (1) performance and environmental effects; (2) dust particle analysis and significance; (3) dust issues on transmissive (glass, plastic) and reflective (mirror) surfaces; and (4) mitigation techniques, including deposition/cleaning mechanics, surface alterations, coatings, and active dust-prevention technologies. Such effects are very important for the economics of the installation (sizing, and the cost–benefit relationships for the cleaning procedures and/or surface treatments). This paper examines issues and previous research within each of these areas, and highlights noteworthy results.

2. Dust effects on glass and transparent materials: transmissive degradation

2.1. Performance: exposure time and environmental effects

Throughout the past 70 years of solar research, the vast majority of studies have been observations of the reduced performance (e.g., power reduction from a PV module) due to dust accumulation and related environmental factors as a function of exposure time at a particular test site or facility. No groups have reported a beneficial effect that dust has had on their solar devices! Based on the observed time-dependent degradation, many authors derived a correction factor or a guideline for cleaning frequency. There is some criticism about the general applicability of such conclusions because dust accumulation occurs at various rates in different parts of the world. Many of these experiments have contradictory results. Furthermore, a significant number of these results are presented as a function of time, but with no evaluation of deposited dust densities or any other particle analysis. However, these historical – often pioneering – reports are still helpful in demonstrating variations in dust conditions and the effects in various regions of the world. They do provide a foundation for more advanced evaluations.

The first consequential studies on the effects of dirt accumulation on the performance of solar collectors were conducted in the United States. Preeminent are studies of Hottel and Woertz [1], who investigated the impact of dust accumulation on solar–thermal systems. Their 3-month test was performed in Boston, Massachusetts, and showed an average of 1% loss of incident solar radiation due to dust accumulating on a glass plate with a tilt angle of 30°. The maximum degradation reported during the test period was 4.7%. They deduced a correction factor – defined as the ratio of the transmittance for an uncleaned or exposed glass plate to that of a clean one – of 0.99, for a 45° tilt angle, based on their experimental investigations; this value was adopted and accepted in the design of flat-plate collectors until the 1970s. Following this pioneering methodology, Dietz [2] and Michalsky et al. [63] also found relatively low reductions in performance in the northeastern United States. Dietz tested glass samples between tilt angles of 0° and 50° to reveal up to a 5% reduction in the solar radiation reaching the collector due to "dirt accumulation." Michalsky compared the performance of two pyranometers in Albany, New York. One was cleaned daily whereas the other was left alone for a testing period of two months. Less than 1% reduction was found for the exposed, not-cleaned pyranometer.

It is important to note that all three of these studies were performed in locations that have frequent precipitation and very low dust quantities in the atmosphere. These ambient conditions also have impact on the relatively small reductions in performance of the solar collectors, and they cannot be generalized to represent dust effects in other regions of the world. However, results from these studies were largely accepted as typical for the US installations, leading to a lack of more-intensive dust-related research and development

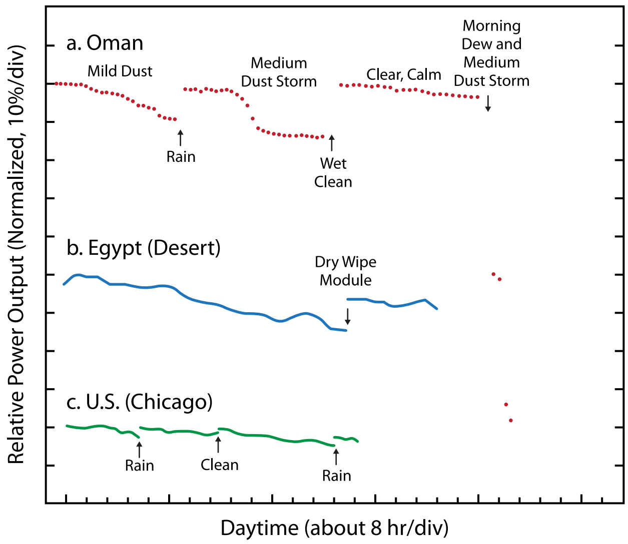


Fig. 2. Comparison of PV module performance under various dust and moisture conditions in (a) Oman, (b) Egypt, and (c) United States (Kazmerski et al., 2010).

(R&D) in the United States until the resurgence of solar energy in the 1970s. In this period, solar technology was also emerging in parts of the world where dust (sand vs. dirt) was a more significant factor. These areas included the Middle East, North Africa, and Asia, where the arid, windy, and dusty environments exacerbate the problem. In these areas, studies have shown that a few hours of exposure can cause the same reduction in performance observed over months in the more temperate and tropical climates.[1] Fig. 2 presents a comparative example, with typical performance as a function of time for a PV module in the United States, Oman, and Egypt.

Several noteworthy studies show large performance variations from location to location as a function of exposure time [5,6,12,25–29,56,87,94,103,130,131,136–138,154,203,215, 217,220,221,224]. Garg [6] examined the effect of soiling on transparent covers used on flat-plate solar–thermal collectors in Roorkee, India. In the study, the reduction in transmittance was measured over a period of days for different tilt angles. He found that the transmittance in the horizontal position (i.e., glass parallel to the ground) was reduced to 30% from its pristine 90% transmission value, whereas the vertical position showed a reduction to only 88% from the 90%. Garg also performed the tests with plastic plates, which showed a greater reduction in transmittance due to greater accumulation of dust. This result is attributed to the rougher surface of the polymer, and possibly some penetration of the dust into the softer polymer surface. A correction factor of 0.92 was deduced from this study. Nimmo and Saed [25] found a 26% to 40% reduction in efficiency for thermal collectors and PV panels, respectively, over a period of six months in Saudi Arabia. Other studies in Saudi Arabia were conducted by Sayigh [12], who found similar but less-conclusive results. He reported a performance reduction of about 30% in flat-plate collectors after only three days without wiping (cleaning). In Kuwait, Wakim (1981) found a reduction of 17% in PV power due to sand accumulation over six days. Sayigh et al. [56] and Hasan and Sayigh [78] performed more-extensive experiments, examining the reduction in transmittance as a function of tilt angle of glass plates for continuous, 38-day exposure in the Kuwait desert. With set tilt angles of 0° (horizontal), 15°, 30°, 45°, and 60°, the corresponding reduction in transmittance was 64%, 48%, 38%, 30%, and 17%, respectively, indicating the critical nature of the angle of the panels' installation. More severe reductions were observed for plastic plates and for reflective surfaces. But, the solar insolation was not used to normalize these data. This group modeled their results with a polynomial fit to their data, which provided a fair model of the transmission loss as a function of days of exposure.

Said [70] evaluated the effects of dust accumulation over a year on a flat-plate solar–thermal, evacuated-tube collector, and a co-located PV panel. Over this period, a 7%/ month power reduction rate was reported for the PV panels, whereas the solar–thermal performance reduction ranged from 2.8%/ month to 7%/ month (attributed to the geometrical effects of the curved, tubular surfaces). Nahar and Gupta [69] conducted studies on solar–thermal glazing plates in the Thar (India) Desert in western Rajasthan, which is reported to be one of the "dustiest deserts in the world" (Payra et al. [203]). Currently, this region is the prime installation target for CSP, concentrating PV (CPV), and possible tracking flat-panel PV to provide as much as 10 gigawatts (GW) of power under India's new "Solar Mission" program[2] to bring 20 GW of solar energy by 2022. To quantify the reduction in transmittance of glass (and in acrylic and polyvinyl chloride [PVC]) used in solar collectors, this group fastened glass, acrylic, and PVC samples to a wooden frame at specific tilt angles from horizontal. The transmittance of the samples was measured before and after cleaning. The PVC was found to suffer the highest transmission loss among the three materials. Over one exposure period of about two months during a period of very low rain, the samples (mounted at tilts of 0°, 45°, and 90°) had corresponding losses: glass (37.5%, 14.1%, 5.2%), acrylic (47.6%, 18.9%, 7.8%), and PVC (55.9%, 44.5%, 20.7%). It was also noted that some PVC samples were degraded (i.e., showed a color change) by the ultraviolet (UV) exposure – and all had a very short lifetime on the order of a year. Dust accumulations in this Thar Desert region certainly require cleaning of the solar surfaces – whether PV or CSP – for any prolonged performance period. This has to be a concern for planned large solar installations in western Rajasthan.

Goossens et al. [82,92] conducted wind tunnel simulations and field experiments to more carefully investigate the deposition mechanics of atmospheric dust on PV collectors. They concluded that wind direction and collector orientation significantly impact dust deposition and distribution, and wind velocities greater than 2 m/s have only a small effect on the distribution of dust deposition. In a laboratory study, El-Shobokshy and Hussein [79] covered PV surfaces with different dust types (i.e., limestone, cement, carbon) and measured the electricity output of the cells under different conditions. An important conclusion was that the effect of dust on the performance of PV panels could no longer be correlated simply to the exposure time in a given site, as suggested by many previous researchers. The results strongly indicated that the nature of the dust– such as dust composition, its size distribution, and the dust deposition density – strongly influences the loss of output power from the PV panels. However, this study imposed some experimental conditions, probably the most important being that all the PV surfaces they prepared were "dusted" under zero-wind conditions. In natural exposures, even low winds significantly affect the sedimentological structure of dust coatings on flat surfaces. Another experimental restriction was that no natural desert dust was used in their experiments; rather, they used limestone, cement, and carbon particulates. The dust deposition density was determined accurately for each experiment, and the finer particles were found to be more "effective" in deteriorating

[1] www.blueplanetbiomes.org/climate.htm

[2] http://mnre.gov.in/pdf/mission-document-JNNSM.pdf.

Table 1
Summary of selected reported dust effects on solar (solar PV and thermal) device performances for the period of 1942 to the present.

Reference	Location	Type of solar device	Period of study	Key findings	Comments and conditions
Hottel and Woertz [1]	Boston, MA, USA	Solar–thermal collectors	3 months	Maximum degradation during the test period was 4.7%	A correction factor of 0.99 (for a 45° tilt angle)
Dietz [2]	NY, USA	Glass samples	3 months	At tilt angles between 0° and 50°, the reduction in solar radiation due to dirt was 5%	
Garg [6]	India	Solar collectors (*glass and plastic covers*)	30 days	For glass, 30% transmittance reduction for horizontal and 2% for vertical positions. Greater reduction was found for plastic	A correlation factor of 0.92 was deduced from the study (45° tilt angle); higher correlation factor for plastic than for glass
Sayigh [12]	Saudi Arabia	Solar collectors	25 days	Heat-collection reduction of 30% after 3 days without wiping	
Anagnostou and Forrestieri [13]	Cleveland, OH, USA	PV modules	1 year	- Degradation is site dependent.- Washing does not eliminate all degradation.- Permanent loss in maximum power reaches a steady value after several hundred days	Local condition is most damaging
Hoffman and Ross [14]	Pasadena, CA, USA	PV module (*glass*)	Laboratory testing	Test procedure for two field-related problems: surface soiling and encapsulate delaminating	
Pettit, Freese, and Arvizu [21]	New Mexico, USA	Solar mirror	1 month	The portable directional reflectometer used to measure the specular reflector loss due to dust accumulation can be limited to a single wavelength	Method to determine solar-averaged reflectance loss from a single measurement at 500 nm
Blackmon and Curcija [16]	California & New Mexico, USA	Heliostat	6 months	Washing heliostat by spray is feasible, and rain and snow could effectively clean it	
Berg [15]	New Mexico, USA	Heliostat	5–6 weeks	High-pressure water spray can recover 95% of the reflectance loss	Mobile system (automated)
Freese [17,18]	New Mexico, USA	Mirrors	7 months	Wind can cause a slight decrease in the reflectance. Melting snow and rain are effective in cleaning dust	Useful correlations with wind, rain; cleaning cycle experiments
Murphy and Forman [26]; **Forman [27]**	Lexington, MA, USA	PV module (*glass*)	18 months	Measurement of soil accumulation and model cleaning using gloss meter	
Nimmo, Saed [25]	Saudi Arabia	Solar collectors& PV modules (*glass*)	6 months	26% and 40% reduction of efficiency from solar collector and PV panels, respectively	Dry conditions
Hoffman and Maag [31]	California, USA	PV module (*glass*)	17 months	To identify key environmental factors that govern soiling levels	Outdoor exposure testing for long durations is the most effective means of evaluating soiling
Roth and Pettit [36]	New Mexico, USA	Mirrors		Reflectance as function of particle size/scattering effects. Small particles are most significant scattering source (< 1 μm)	Reported effectiveness of surface coatings and electrostatic biasing for mitigation. Wind tunnel studies
Cuddihy [39]	Pasadena, CA, USA	PV module	Theoretical study	Describe known and postulated mechanism of soil retention on surfaces	Dust morphology/size data
Pettit and Freese [40]	New Mexico, USA	Mirrors	10 months	Deposited particles are much more effective in reflecting particles than absorbing it	Force mechanisms proposed and investigated for dust adhesion
Zakhidov and Ismanzhanov[37]	USSR	Mirrors	Experiment	Strong wind with driven dust causes damage to the surface of the mirror	
Wakim [46]	Kuwait	PV modules (*glass*)	6 days	17% reduction in efficiency of modules	
Roth [46]	New Mexico, USA	Mirrors	Up to 10 months	Reflectance losses as function of wavelengths of incident light and of particle size/distribution	Differences in particle distributions between day and night due to soluble nature of the particles. Morphology data. Adhesion forces
Bethea et al. [50]	Texas, USA	Solar concentrator	Laboratory experiment	Reflectivity expected to decrease by 2.4% per year due to dust storm conditions	Simulated studies; Accelerated lifetime test development
Sayigh et al. [56]	Kuwait	Glass, plexiglass, stainless steel, mirrors	38 days	64%, 48%, 38%, 30%, and 17% transmittance reduction for 0°, 15°, 30°, 45°, and 60° tilt angles, respectively	Dust particle topography, dust size evaluations

El-Shobokshy et al. [57]; **Zakzouk [52]**	Saudi Arabia	CPV	1 month	Open-circuit voltage did not change, and short-circuit current and cell efficiency showed a large change with dust deposition	Concentrating PV study; effect on dust accumulation on cell temperature investigated; Modeling of series resistance effects
Berganov et al. [60]	USSR	PV cells	6 months	Effect of soiling on solar cell power production is high	
Bajpai and Gupta [64]	Nigeria	Silicon solar cell	4 months	Poor efficiency due to scattering of incoming radiation by dust particles	
Michalsky [63]	New York, USA	Pyranometers	2 months	1% reduction for the exposed, not-cleaned pyranometer	
Ryan et al. [67]	Oregon, USA	Solar module array (*glass*)	6 years	Unwashed solar cell array has degraded at a rate about 1.4% per year	Fluctuations in degradation (rates) do exist and long-term testing of degradation is needed
Said [70]	Saudi Arabia	Solar collectors& PV modules (*glass*)	1 year	7% reduction per month for PV panels and 2.8% to 7% for solar collectors	
Deffenbaugh et al. [59]	6-sites, USA	Parabolic solar collectors		Long-terms exposure testing for reflective and transmissive loss evaluation. Developed prediction method based upon modeling of results. Wash frequency and optical degradation rates are used as primary inputs to model long term observations.	Used various sites to establish independence of methodology to any specific location. (Oregon, Georgia, Texas (2), Ohio, California, New Mexico)
Al-Alawy [71]	Baghdad, Iraq	Horizontal surface (*glass*)	9 years	Higher percentage of cumulative dust leads to an energy reduction of 50% or more	Good correlations with wind speed and dust accumulations; good base of daily and hourly solar radiation used for models
Nahar and Gupta [69]	India	Solar collector	18 months	Annual reduction in transmittance for daily cleaning cycle was 4.26%, 2.94%, 1.36% and for weekly cleaning cycle was 15.06%, 9.88%, 3.28% for glass at tilt angles of 0°, 45°, and 90°	Examined glass, vinyl, acrylics—glass is superior under dust conditions. The data raise concerns about locating large solar power plants without including strict cleaning plans
Hassan and Sayigh [78]	Kuwait	Glass	38 days	64%, 48%, 38%, 30%, and 17% transmittance reduction for 0°, 15°, 30°, 45°, and 60° tilt angles, respectively	Spectral report that all wavelengths are affected
Pande [77]	India	PV module (*glass*)	1 year	Reduction in current value due to dust was up to 30%	
Goossens et al. [82]	Israel	PV module (*glass*) and mirror	Laboratory work	Wind direction and panel orientation have a serious effect on dust deposition and distribution. A wind velocity of greater than 2 m/s has only a small effect on dust distribution	Wind tunnel experiments. Correlated these with real conditions
El-Shobokshy and Hussein [80]	Saudi Arabia	PV modules (*glass*)	Laboratory work	Dust material, size and deposition density has a strong effect on loss of output power	PV surface prepared under zero wind velocity and no natural desert dust was used
Alamoud [81]	Riyadh, Saudi Arabia	PV module (*glass*)	1 year	Efficiency decreased by 5.73% to 19.8% depending on the type of the module when exposed to outside environment	Compared module specifications to manufacturer's claims (differences). Hot, arid conditions
El-Nashar [85]	United Arab Emirates	Evacuated-tube collector	1 year	Monthly percentage in glass transmittance decline is seasonal: 10% in summer and 6% in winter. Reduction of 70% of collector performance when left without cleaning for one year	Hourly and monthly data acquired
Bowden et al. [86]	Sydney, Australia	PV roof tiles and concentrators	Laboratory work	Dust affects the energy conversion to a small degree. Examined effect of dust on the loss in internal reflectance of the CSP roof units. Total losses less than 1.3%	Part of a larger study on performance of PV products for rooftops. Data for coastal and in-land locations/ residential/commercial
Adanu [88]	Ghana	PV system (*glass*)	4 years	Effect of dust particles in atmosphere generally reduces the solar irradiance and the energy output from the PV array	Time of day data reported. Cleaning by wiping of module surface
Kattakayam et al. [102]	India	PV module (*glass*)	Laboratory work	The loss of power due to accumulation of dust and the increase in temperature of the panel can be significant	Careful analysis of IV characteristic from operating PV field. Provides information on instrumentation for monitoring
Becker et al. [109]	Cologne, Germany	PV cells	Laboratory work	The pollution leads to a partial shadowing of the cells reducing the output	This pollution has minor effects on PV operation ($<4\%$)
Hammond et al. [108]	Arizona, USA	PV module (*glass*) and radiometer	16 months to 5 years	Soiling effect on PV module increase as the angle of incident increases. Losses increased from 2.3% at normal incident to 4.7% at 24° and 8% at 58°. For	Extensive soiling data on PV modules and radiometer outputs

Table 1 (*continued*)

Reference	**Location**	**Type of solar device**	**Period of study**	**Key findings**	**Comments and conditions**
				radiometer, lost more than 2% due to soiling, and up to 8% due to bird droppings	
Offer and Zangvil[107]	Israel	Mirrors	1 week in May, 1990	Airborne particle accumulation on solar mirrors decreases the reflectivity and the mirror efficiency. Reflectivity reductions greater than 90%	Desert testing, including dust storm data
Goossens, Van Kerschaever [117])	Israel	PV modules (*glass*)	Laboratory work	Fine dust deposition on the cell has significant effect on power output. Considered effects of due to airborne dust concentration and wind velocity. Reported losses in solar intensity on cells, open-circuit voltage, fill factor, short-circuit current and power as function of accumulation time. Power losses greater than 95%	Reported *I–V* characteristics as a function of the dust density
Mastecbayeva and Kumar [124]	India	Glass	30 days	Transmittance dropped from 87.9% to 75.8% over the 30-day period	
Biryukov [119,123]	Israel	Mirror	Laboratory experiments	For measurement of dust influence on reflector, the experiment showed the intensity of concentrated light; confirmed result of measurement with specular reflectometer	Used three different techniques to determine dust effects on specular properties of parabolic concentrator
Asl-Soleimani et al. [131]	Tehran, Iran	PV system	10 months	Air pollution can reduce the energy output of solar module by more than 60% in a city like Tehran	PV module output monitored as function of time of day under "pollution" conditions
Hegazy [130]	Egypt	Glass plates	1 year	Solar transmittance as function of tilt angles. Vertical plates had dust with diameters <1 μm only. Compared a calculated "dust factor" (correction factor) to the observed one. Loss in transmittance typically 75–80% over a month's exposure	Plates purposely not cleaned over 1-month periods. Compares data to reports from India and Kuwait
El-Nashar [136]	Abu Dhabi, United Arab Emirates	Evacuated-tube collectors (*glass*)	1 year	Drop in transmittance (0.98 under "clean" condition to 0.70), causing as much as 40% drop in distillate production. (Need to supply 38% more power from conventional electricity generation)	Application is a solar desalination plant (1864 m^2 collector field); Seawater distillation with 120 m^3/day capacity
Badran [139]	Arizona, USA	Mirrors of telescope	3 years	Coating for 3 years exhibited 5%–7% drop in reflectivity at 310 nm and no decease in other wavelengths. Water washing is the best cleaning method	Cleaning methods developed for Cherenkov telescope at Mt. Hopkins
Hassan et al. [139,140]	Saudi Arabia	PV modules (*glass*)	6 months	33.5% and 65.8% reductions in efficiency after 1 month and 6 months	
Kobayashi et al. [142]	Tokyo, Japan	PV module (*glass*)	Laboratory experiments	Changing the aspect ratio of PV cell used for PV module results in degradation output of 80% or less with 3% of spot dirt on the module area	Primarily "dirt spot" analysis; Some correspondence to the shape of the solar cell in the module. Also, studied cell circuit-configuration effects
Elminir et al. [147]	Helwan, Cairo, Egypt	PV cells and glass	7 months	Decreases in PV output of about 17.4%/month	Provides information as a function of tilt angle. Includes a chemical analysis of the dust
Kimber et al. [148]	California and South-western USA	PV system (grid-connected)	~1 year	"Soiling" study for utility-connected PV system. Efficiency and energy losses (typical 0.2% per day without rainfall)	Restorative nature of rainfall well documented. Various locations provided in these portions of USA
El-Nashar [173]	Abu Dhabi, United Arab Emirates	Evacuated-tube solar–thermal collectors *(glass)*	1 year	Seasonal losses due to dust at 14%–18%	Updated and seasonal data following El-Nashar (2008); solar desalination plant; automated data acquisition
Al-Helal and Alhamdan [174]	Saudi Arabia	Polyethylene covers	13 months	Reduction in global solar radiation was 9% after 1 month, then reduced to 5% after 11 months due to rainfall in the area	GSR and PAR transmittance evaluations; application to greenhouse enclosures
Clark et al. [176])	MD, USA	Lunar dust control	Laboratory experiments	Design a compact device <5 kg mass and using <5 W to harness the dust for sampling as part of the	

				extended exploration of Mercury, Mars, or other regions of the solar system	
Vivar et al. [181]	Madrid, Spain; and Canberra, Australia	CPV system (various lenses)	4 months	CPV system more sensitive than flat-plate PV to dust accumulation. Up to 26% loss after 4 months exposure	Dust is critical factor for CPV performance
Yerli et al. [186]	Istanbul, Turkey	PV modules (*glass*)		Derating parameters reported for temperature and dirt; dust has most significant effect	750 Wp system
Mani and Pillai [184]	Bangalore, India	PV module and system	Review article	The paper includes two phases of research appraisal. Phase I from 1960 to 1990, phase II for post 1990. Table has been developed to guide in the identifying appropriate cleaning/ maintenance cycle for PV systems in response to the prevalent climatic and environmental conditions	Detailed review provides excellent guidance for cleaning and mitigation cycles
Miller and Kurtz [202]		CPV Fresnel lenses	Review article	Primary look at PMMA lenses (some silicone-on-glass). Detailed examination of the loss mechanisms and durability. Soiling review included definitions, variation of reflectance with time, inclination (tilt), wavelength, the mechanisms of adhesion and accumulation, moisture, particle size and distribution, and prevention/soiling	Comprehensive examination of soiling of Fresnel lenses for CPV. Paper has much wider examination of the durability and degradation issues with the Fresnel lenses beyond the dust issues
Ju and Fu [200]	Chongqing, China	PV modules (*glass*)	$\sim$ 1 year	PV "fouling coefficient" proposed (0.985 during rainy season and 0.958 during dry season)	For PV project, proposed important considerations for dust in 3 stages of development: (1) Planning; (2) Design, and (3) Operation
Ibrahim [196]	Laboratory Tests and Kuwait	Solar cells (large-area 10 cm $\times$ 6 cm)	10 days	Current losses of $>13\%$ and voltage losses of $>0.86\%$ (5%–15% loss in peak power)	Also studied shadowing of cells
Cabanillas and Munguía [195]	Hermosillo, Sonoro, Mexico	Crystalline and amorphous Si PV modules	90 days (August through December)	4%–7% reduction in power for crystalline Si modules and 8%–13% for amorphous-Si modules. Demonstrated sensitivity to module technology type	Particle-size analysis as part of study. Careful analysis of relationships between particle size and volume percent of that size occurring
Sulaiman et al. [194]	Malaysia	PV modules	Laboratory experiment	18% or reduction in peak power when depositing dust on PV module. 6% power reduction difference between mud and talcum deposition	
Zorrilla-Casanova et al. [197]	Spain	PV module (*glass*)	1 year	In dry seasons, energy losses exceed 20% over 3-month periods. Annual average losses in PV output were 4.4% (with natural cleaning by rain). Proposed regular, periodic cleaning scheduled for modules	Provided simple model, simulated with ray-tracing methods to explain the behavior of dust-induced loses in solar PV modules. Looked at both fixed and tracking systems of PV panels; Evaluated time-of-day losses
Pravan et al. [201]	Italy	PV system (1 MW)		Investigated two 1-MW PV systems; Soil type and washing technique control the losses. 6.9% loss with sandy soil and 1.1% with more compact soil	All measurement under STC. Regression model used (superior to performance ration which is influenced by seasonal variations in temperature and plant availability)
Jiang et al. [209]	China	PV module (*glass*)		Dust deposition layer 0 to 22 g/cm^2, PV efficiency decreased by 26% (linear relationship). No difference between cell types	Note that modules encapsulated with epoxy (organic) degrade more
Kaldellis and Kapsali [206]		PV generators	Modeling	Examined microgrids. Distributed systems are shown to have as much as a 12% better performance under dust conditions than a central station	Modeling study for grid
Qasem et al. [197]	Kuwait	CdTe thin-film PV modules	Outdoor tests and modeling	Examined effect of dust densities o performance (in vertical and horizontal module configurations), with latter having increase risk of hot spots with dust deposition	Showed effects of moisture/dust in photos. Provided modeling of IV characteristics with dust deposition (using PSPICE)
Al Busairi, Möller [185]; Al-Busairi and Al-Kandari [62]	Kuwait	Glass surfaces on various PV modules	Outdoor tests	Demonstrated that the decrease in power from PV module depends on the angle between the incident sun (photons) and the normal to the panel	Loading depends on the tilt angle and is non-uniform over module surface (time of day dependences)
Mekhilef et al. [219]	Malaysia	Solar cells and modules	Laboratory and modeling (2-month periods)	Examined the literature for dust effects on performance as function of tilt. Reported average drop in performance (power): US 1–4.7%; Saudi	Dust containing minute pollens, bacteria, fungi, microfibers (carpets and fabrics), vehicular and volcanic activity (specific to this region) Effects of moisture

Table 1 (*continued*)

Reference	Location	Type of solar device	Period of study	Key findings	Comments and conditions
				Arabia 40%; Kuwait 65%, Egypt 33.5–65.8%, Thailand 11% (1 month)	
Mohamed and Hasan [223]	Libya	PV modules	Outdoor testing	PV modules exposed for a period from February through May in Sahara environment. Reported significant though gradual reduction in power. Cleaning procedures	Object of study is to evaluate the cleaning needed to keep the PV output at a sufficient level. Weekly washing (water) kept power loses in the 2%–5% range
Qassem et al. [218]	Kuwait	PV modules	Outdoor testing	Investigated effect of dust on PV modules with respect to concentration and spectral transmittance. Examined a-Si:H, CIGS, and crystalline Si technologies	Provided interesting information on the spectral effects of the dust. Showed that because of this, wide-bandgap technologies are affected more than lower bandgap technologies

the performances. Interestingly, these authors also noted that the carbon particles having oil present from power plants were the worst contaminant for output power from the modules. These experiments are discussed in more detail later in this paper. El-Nashar [85] compared the effect of dust accumulation in the United Arab Emirates on the performance of evacuated-tube and flat-plate types solar–thermal collectors over different time periods, extending from one month to a year. A decline in glass transmissivity is seasonal, between greater than 10%/month during summer and about 6%/month in winter. However, a 70% reduction in the collector performance was observed when the collector was left without cleaning for the entire year.

Hammond et al. [108] found that soiling effects on modules increase as the angle of incidence increases. Losses increased from 2.3% at normal incidence to 4.7% at 24° and 8% at 58°. (Interestingly, it was noted that bird droppings were a more serious cleaning issue than soiling due to dust and dirt.) Goossens and Kerschaever [117] carried out wind tunnel experiments to evaluate the combined effects of wind velocity and airborne dust concentrations on the solar cell. They discovered that the fine dust particles interact with the antireflection coating on the cell surfaces and cause irreversible damage. The effect of dust deposition on the transmittance of the glazing material was also studied by Mastekbayeva and Kumar [124] under tropical climate conditions. They reported that the transmittance dropped from 87.9% to 75.8% over a period of 30 days. Hassan et al. [141] showed that degradation progresses more rapidly during the first 30 days of exposure. The results imply that the PV module efficiency decreases 33.5% after one month and further drops to 65.8% of its initial value after six months without panel cleaning. Kimber et al. [162] presented a new model for predicting the energy loss of PV systems from the accumulation of dirt and particulate matter on PV modules. The empirically derived model incorporates hourly energy simulations that use typical meteorological-year data files and typical rainfall data to predict energy performance. They found that the PV system efficiency declines by an average of 0.2% per day without rainfall in dry climates, equating to an annual energy loss between 1.5% and 6.2% depending on system location. Table 1 summarizes and compares their research results with a number of other similar studies conducted worldwide, investigating the effects of dust accumulation and conditions on solar device performance.

Despite this exceptional body of experimental information, much remains to be understood about the complex relationship between dust and performance of these solar devices—and more importantly, the mitigation of these issues. Primarily, the deposition rates were the controllable and/or measurable parameters in these studies. In some cases, these rates can be misleading due to climate conditions (e.g., precipitation, windstorms) that were not always noted during the outdoor exposures. Even more fundamental, the issues relating to the forces holding the dust to the surface and the materials that may be in the dust (e.g., organic matter) that hold the particles together have only begun to be investigated and understood. Overall, these performance studies have been foundational in providing a database and guidance for further research and experiment design.

2.2. Dust deposition and PV device characteristics

Understanding the relationships between the physical properties of dust particles (e.g., size, geometry, and chemistry) and the performance of a solar collector (panel) is potentially the critical key to develop effective mitigation and prevention techniques. In Section 4, we address the chemistry, topology, and morphology of dust particles. Of course, the physical nature of the dust and the deposition characteristics are governed by the region of the world

in which the dust studies are conducted. The interrelationships among the dust parameters and the deposition and subsequent device performance were not recognized and validated until the early 1990s. The principal investigations and results are highlighted in this section.

El-Shobokshy and Hussein [79,80] were among the first to perform investigations in a controlled laboratory environment, during which the experimental parameters could be maintained, measured, and reproduced. The purpose of their studies was to investigate the physical properties of dust particles accumulated on the surface along with deposited-layer density, and subsequently, to correlate these parameters with the degradation in the performance of the PV module. They used five varieties of "laboratory-defined" dust having distinct and identified physical properties and constituents that are frequently present in the atmosphere. Of these, three were limestone-based, ground into three different grades. Cement was selected because of its presence in major building materials, and it is present in the air in most populated areas. It also is a problem in areas where cement is manufactured. Carbon was chosen because it is the product and a major pollutant in most combustion processes. Table 2 summarizes the size distribution of the dust types that were evaluated.

Table 2
Results of size distribution analysis of the test dusts (El-Shobokshy and Hussein [79]).

Dust type	Mean Diameter (μm)	Standard deviation
Limestone		
Grade I	80	1.29
Grade II	60	1.25
Grade III	50	1.28
Cement	10	1.18
Carbon	5	1.136

The laboratory experiments were performed using simulators (tungsten-halogen 1000-W lamps, providing about 195 W/m^2 onto the module surface) to control as many of the factors as possible and to ensure reproducibility. Baseline current–voltage (I–V) characteristics (measured at device temperatures between 30°–32 °C) for a commercial, crystalline-silicon module were documented for different light intensities. The dust was blown onto the clean panel using dry air, and sufficient time was allowed for the particles to settle. The uniformity of the dust on the panel was checked under a microscope. The dust-deposited-layer density was determined by wiping the surface with a number of wet (water) rubber pieces of predetermined mass to collect all of the dust particles. The pieces were then placed in a dryer for 24 h to evaporate the water. A precision microbalance is the instrument of choice in determining surface [g/cm^2] or volume [g/cm^3] dust densities. It measured the weight of the dust by determining the difference before and after dust collection. This mass of the dust is divided by the surface area of the module (or the area from which the dust was collected) to determine the deposition surface density. The process was repeated several times for various densities of each type of dust.

Four important parameters were measured as a function of deposition density: short-circuit current, power output, reduction in solar intensity (transmission), and fill factor (see Figs. 3 and 4). The results presented in Fig. 3 show that the short-circuit current and power output have similar trends because the open-circuit voltage is not affected by the dust accumulation (unless the dust layer was thick enough to totally block the light).

From the performance characteristics in Fig. 3, the degradation in the PV performance depends not only on the dust deposition, but also, on the kind of dust and its size distribution. Finer dust accumulation on the surface has a much greater negative effect on PV performance (for every case) than that of coarser particles.

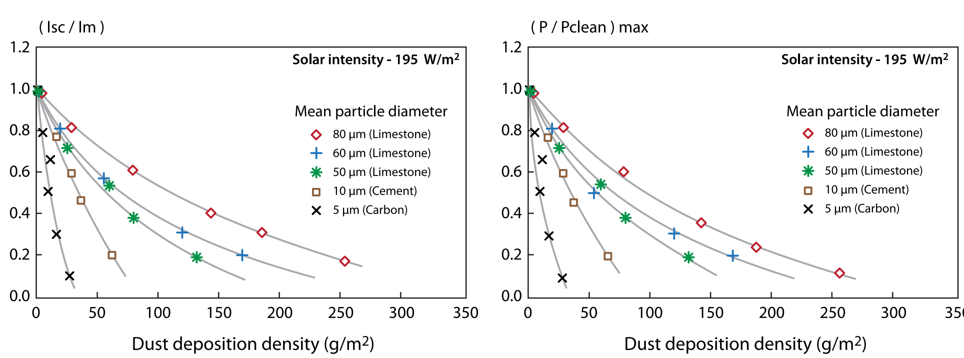


Fig. 3. Short-circuit current (left) and power output (right) for various particle sizes as a function of dust deposition density (El-Shobokshy and Hussein [79]).

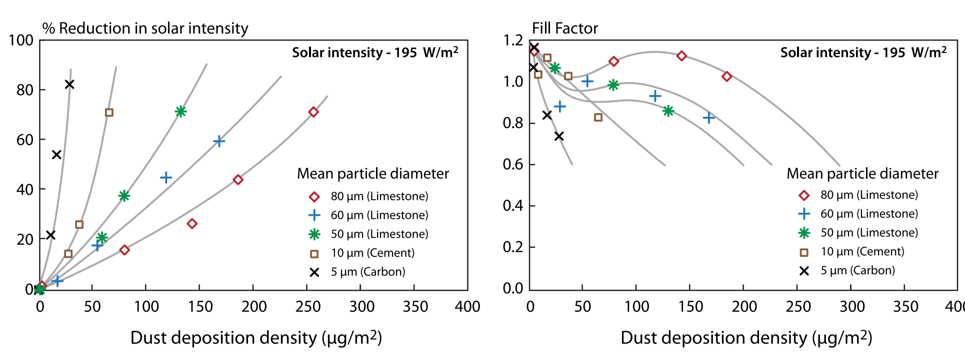


Fig. 4. Reduction in solar intensity (left) and fill factor (right) for various particle sizes as a function of dust deposition density (surface density in g/m^2) (El-Shobokshy and Hussein [79]).

This is attributed to the more uniform manner by which finer particles are distributed than that for the coarser ones, thus minimizing the voids between the particles through which light can pass. The short-circuit current is reduced to 20% of its initial value for the carbon accumulation with only 28 g/m^2, as compared to 73 g/m^2 for cement, and 125 g/m^2 for 50-μm, 168 g/m^2 for 60-μm, and 250 g/m^2 for 80-μm limestone dust. It was also noted that the specific dust material also affects PV performance. For example, carbon particulates absorb solar radiation more readily than the other dust (limestone, cement) types. This can affect not only the amount of light reaching the solar converter, but also, the temperature of the converter.

Fig. 4 also shows that for limestone particles greater than 40 g/m^2, the fill factor (FF) initially decreases and then increases, reaching a local maximum before decreasing again as more dust accumulates. El-Shobokshy and Hussein [80] concluded that "with little amount of coarse dust deposition, the particles cannot cover the whole surface area and appreciable void areas would exist. During this stage of dust deposition, the uniformity of light passing to the cell is questionable and a situation similar to partial shadowing would be created. Under the circumstances the temperature of the cells will be subject to non-uniform changes, thus decreasing the FF. However, as the dust deposition increases and all voids are covered with particulates, the diffused component of light increases and the light reaches the cell in a more uniform manner, the FF increases to some level. As the deposition process proceeds to a thicker layer, then the light reaching the cells is reduced, and the FF once again decreases."

Finally, El-Shobokshy and Hussein [80] identified the three key factors that contribute to PV performance deterioration:

1. Principal dust material (chemical composition)
2. Size distribution of the dust particles, which may be represented by mean diameter and the standard deviation
3. Dust-deposited-layer density on the panel surface (which depends on the parameters in factors 1 and 2).

Furthermore, they discovered that for the same constituents, fine particles have a greater effect on the performance of PV cells than that of coarser ones because of their ability to more effectively screen the incident sunlight. This is discussed in more detail in Section 4.

Mailuha et al. [87] expanded on the El-Shobokshy and Hussein [77] investigations as part of their engineering-based evaluation on solar-energy use in Kenya. Their PV module-based study focused on the effects of dust-deposited-layer density and included tilt angle and solar intensity. They found that as the solar intensity increased, the PV performance degradation due to dust accumulation decreased. At 700 W/m^2, the reduction in power output was almost negligible; however, when the intensity dropped to 400 W/m^2, the reduction was nearly 25% of the initial power output. Fig. 5 presents their principal results. Wilson and Ross reported similar results [49].

Goossens et al. [79] and others [71,82,92,117,215,219,220] reported a series of studies focusing on the effects of wind velocity, wind direction, and airborne dust concentrations on solar collectors. The 1993 study (discussed in the previous section) and the 1995 study considered the effects of wind velocity, wind direction, and diurnal rotation for a solar–thermal collector in the Negev desert, Israel. In that region, winds typically originate from the N, NW or W, so the wind directions under test were N10E (North, 10° toward East), N35W, N80W, and S55W. The diurnal rotation was determined by orienting the mirrors to track the sun throughout the day, and measurements were taken at sunrise, forenoon (i.e., the morning period), solar noon, afternoon, and sunset. They found that the higher wind speeds resulted in greater depositions, which may be a result of increased particle flow and high turbulence. For the effect of wind direction and collector position, they found that for all wind directions, noon (small inclination) accumulated the highest dust deposition. Sunrise and sunset (large inclination) resulted in the lowest deposition. This was a direct consequence of the inclination angles of the collector throughout the day. They also observed that the wind direction had a peculiar result on the individual mirrors in an array. For N and NW winds, the deposition increased for each eastward mirror except for the last mirror. The W and SW winds, however, accounted for a more symmetrical deposition, with the greatest thicknesses at the central mirrors.

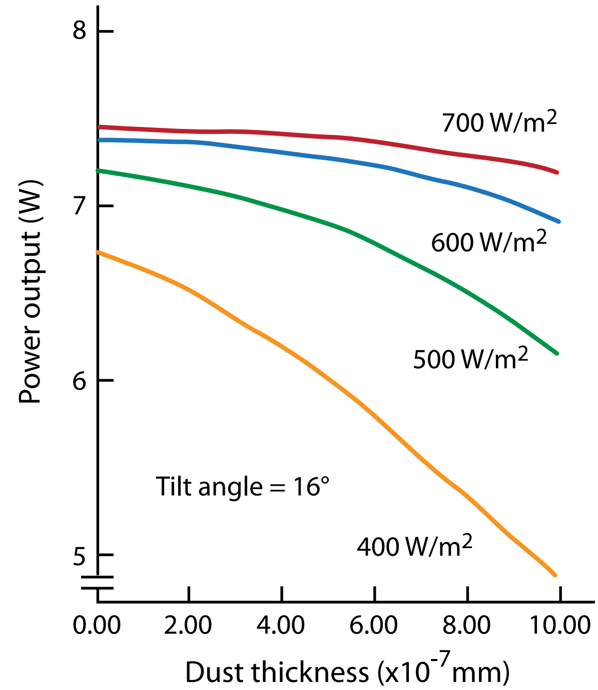


Fig. 5. PV module power degradation for various solar intensities as a function of dust thickness (Mailutha et al., [87]).

Goossens and Kerschaever [117] conducted a much more elaborate and controlled study using wind-tunnel simulations. The intention was to evaluate both the aerodynamic and sedimentological effects that wind speed and airborne dust concentration have on PV cell performance. The silicon PV modules were tested in the larger portion of a closed-return-type wind tunnel. The dust was a natural soil prepared from local soil, which was composed of 95% silt (2–62 μm) and 5% clay ($<$ 2 μm), with an overall average diameter of 30 μm. For each set of tests, the short-circuit current, open-circuit voltage, power output, reduction in solar intensity, and fill factor were measured. The results showed that as wind velocity increased, so did the dust deposition—complementing their previous observations in the Negev desert. The same was true for increasing airborne dust concentrations. The decrease in PV performance is a direct result of observed increased dust deposition. The aerodynamic effect is the relationship between the wind velocity and sedimentation rate. For this case (constant dust concentration), the sedimentation on the PV cell is directly proportional to the free-stream wind velocity, accounting for the drop in PV performance with increasing wind velocity. The sedimentological effect describes the behavior in which the dust settles on the surface. Rippling effects were observed on the soiled surface, with ripple spacing directly proportional to wind velocity. Ripple height and sedimentation time are inversely proportional to that parameter. This phenomenon has a minor effect on the transparency of the dust coating and is negligible compared to

aerodynamic effects. Goossens et al. recommended that PV modules in deserts and other areas with high soiling conditions should be installed in locations where wind velocities and airborne dust concentrations are low—certainly a logical prediction. Field measurements in the Negev desert have shown that dust accumulation in the leeside (i.e., facing away from wind) of hills may be up to four times less than on windward slopes, and 50% less than on flat horizontal surfaces.

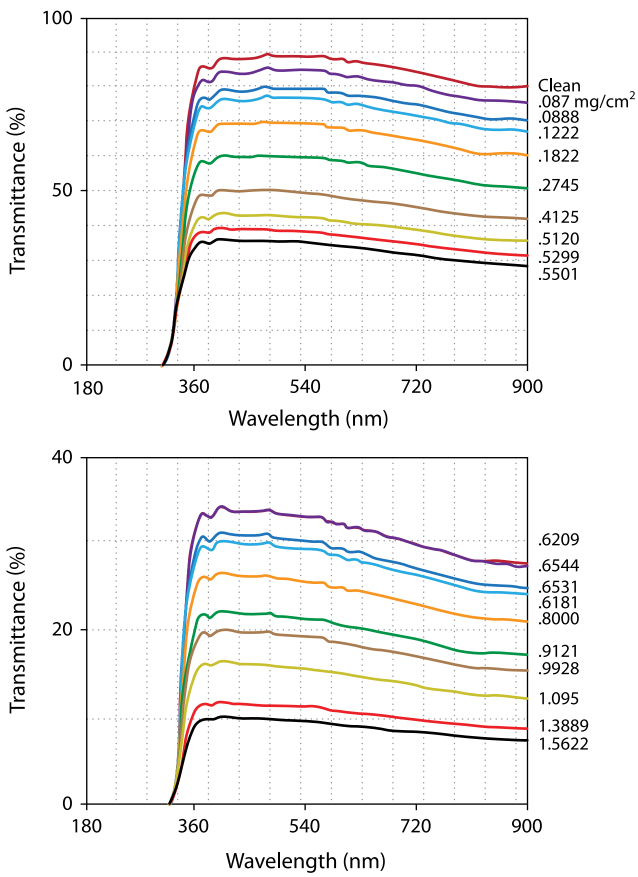


Fig. 6. Spectral transmittance of light through glass with as a function of sand dust accumulations: (a) expanded to show lower accumulations and (b) higher accumulations (Al-Hasan [114]).

Al-Hasan [114] reported both experimental and analytical evaluations (conducted at the Laboratory for Experimental Geomorphology, Katholike Universiteit, Leuven, Belgium) of the effect of sand dust layer on beam light transmittance at a PV module glass surface. He understood that the relationship between dust accumulation and light transmittance is necessary to determine for proper design of and mitigation in PV systems. But rather than examining dust accumulation in different weather conditions, he used a controlled process allowing known dust accumulations so that reproducible tests could be conducted. In his experimental part, Al-Hasan and Ghoneim [140] designed a simple but elegant experiment conducted within a custom plywood sand box (66 cm × 100 cm × 143 cm). Inside this enclosure, metal stands were constructed to elevate the glass samples from the box floor. A sand-dust blaster (using compressed air) transported sand from outside the box to the inside, with a diffuser to suspend the particles without high air speeds affecting the glass samples. Several iterations were conducted with increasing amounts of dust being deposited on the glass samples. Transmittance and reflectance were measured using spectrophotometers for varying wavelengths between 0.18 and 0.9 μm. The measurements show that the transmittance decreases as the dust concentration increases with no wavelength dependence (Fig. 6).

Fig. 7 presents wavelength and dust concentration effects. As the dust-particle concentration on the glass sample increases, a larger amount of longer-wavelength radiation is reflected compared to the shorter-wavelength radiation. Reflectance increases rapidly until the dust concentration reaches 1 mg/cm^2, after which the reflectance increases at a slower rate. This behavior is explained by the fact that sand dust starts to fully cover the glass when it reaches this dust concentration level. Al-Hasan and Ghoneim [140] explain the reflectance at longer wavelengths because the color of the sand particles is a reddish brown.

Elminir et al. [147] conducted one of the most comprehensive and revealing studies involving dust effects on solar collectors. Transparent covers of solar collectors were evaluated in Cairo, Egypt, from December 2004 through June 2005, examining the effects of tilt angle, orientation of exposure, climate, deposition density, and mineralogy of the dust. The research was conducted at the National Institute of Astronomy and Geophysics, within an industrial area in which several cement factories were co-located. A special apparatus (Fig. 8) was constructed to hold 10 cm × 10 cm glass samples at eight different orientations: N, NE, E, SE, S, SW, W, and NW, and seven tilt angles between 0°

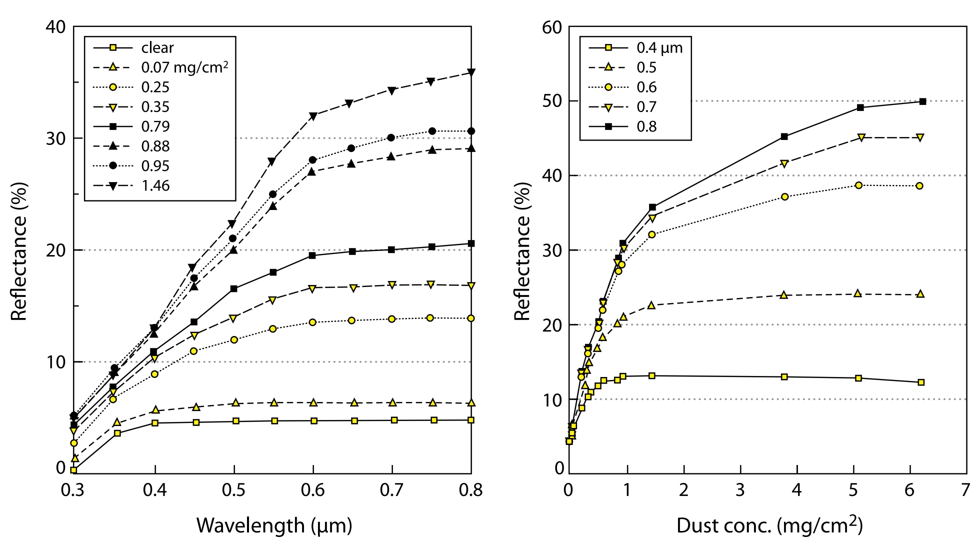


Fig. 7. Reflectance of dusty glass for different dust amounts as a function of wavelength (left) and dust concentration (right) (Al-Hasan [114]).



Fig. 8. Experimental apparatus exposing glass samples to seven tilt angles and eight different orientations (Elminir et al. [147]).

and 90° at 15° increments. Calibrated PV solar cells behind the glass—to alleviate uncertainties due to spectral content and intensity—were used to monitor degradation in performance due to the dust impact and accumulation.

The climate in this region was considered to be a major contributing factor for these studies, and the conditions were well documented. It was observed that large temperature differences promoted dew formation at dawn, with the relative humidity being high—fluctuating between 41% in May and 62% in January. Dew promotes dust accumulation on flat surfaces, and subsequent evaporation reinforces dust adhesion; in fact, it sometimes forms a solid, packed cement-like composite. The average wind speeds in this region were 3.7 m/s and gusts up to 5–6 m/s, which helped propel the dust onto the surfaces, with the dust mass measured using a mass microbalance. His compositional and chemical analysis of the dust is described in Section 4.

Elminir's results confirmed the strong dependence of dust deposition on the transmittance and on energy yield concluded in previous studies (see Table 1). Elminir et al. correlated the orientations with the tilt angles as presented in Fig. 9. As expected, as the tilt angle increases, the dust deposition decreases because the particles tend to roll or fall from the surface under the influence of gravity. The quality of the dust accumulated on the glass at different orientations with the same tilt angle was reported to be approximately equal. Again, as expected, the sample oriented NE at a 15° tilt angle accumulated greater dust (8.02 g/m^2) than any other orientation because of the influence of the more prevalent NE winds, which were reported to coincidently bring the emissions from the local cement factories (Section 4).

The reduction in transmittance in the glass samples increases gradually before saturating, as observed in Fig. 10. For the northeast-facing samples (i.e., those directed toward the cement factories), the reduction in transmittance was maximum for glass samples having tilt angles of 15° (20.89%), 30°(18.86%), 45°(18.32%), and 75°(13.97%).

One artifact of these studies was unexpected: a transparent layer of dissolved and subsequently re-crystallized salts accumulated on the surface of the glass. The layers grew over time and eventually became too thick to be dissolved by the rain. This morphology (Fig. 11) had some major effects on the optical measurements. The transmittance reductions and deposition densities were measured for this set of samples and the results are summarized in Table 3.

The purpose of studying the influence of dust deposition on the PV energy yield was to gain some quantitative understanding of the rate at which desert dust causes degradation of the output of non-maintained PV modules. Many of the applications in Egypt, for example, are for remote desert farms and villages in which only periodic maintenance can be expected. The PV output was quantified as a function of the quantity of the settled dust in conjunction with plate tilt angle, and the orientation of the surface with respect to the dominant wind direction. The effects of the two rainy periods, in January and March, can be observed in these 6-month tests. Figs. 12 and 13 presents the sequence for the modules at various orientations.

These PV energy-yield experiments replicate the results of those performed in some earlier research. The experiments do still have uncontrollable factors. The behavior of the degradation in Fig. 12 can also be attributed to geometric influence rather than dust accumulation alone. Only the south-facing panels—the orientation needed for maximum solar use—indicate significant degradation due to soiling.

The results confirmed that the reduced transmittance normal to the glass depends strongly on the dust deposition density in conjunction with tilt angle, as well as on the orientation of the surface with respect to the dominant wind direction. Thus, as the dust deposition density goes from 15.84 to 4.48 g/m^2, the corresponding transmittance diminishes from 52.54% to 12.38%. Obviously, large transmittance reductions are encountered as the tilt angle is decreased and can be attributed to the increase in dust deposition on the plate. Further, significant degradation occurs in glass transmittance for the glass sample having a tilt angle of 15° and oriented with a 45° deviation from north. One explanation is that the northeast winds affect the atmosphere by carrying fine particles of various origins, but assumed to be mainly from the emissions from the local cement factories.

During the most recent 15 years, the understanding of dust and its characteristics, control, and effects on PV panel performance have been advanced from research conducted from an unexpected source—one beyond the boundaries of our planet [73,76,96,160,192]. In preparing for the planet Mars missions, dust was known to be a potential problem from information first gained from the two Viking Mars landers in 1976. Dust, of course, has an additional problem because there is currently no human capacity to clean the PV panels on Mars! Landis [84,89,106,111], Landis et al. [90,105] and Landis and Jenkins [95,110] conducted extensive evaluations of the effects of Mars dust on the performance of PV panels in preparation of placing of the first Mars rover (Sojourner) on July 4, 1997. Sojourner performed its experimental tasks for almost 3 months; then the rover's communications ceased, likely due to heavy dust conditions that obscured the solar panels. The second Mars Exploration Rover (RER) mission in 2003 was preceded by substantial investments in research and technology development to evaluate the extent of dust on the performance of the PV panels and possible mitigation of the problems. The Spirit and Opportunity rovers began their careers in 2004 and benefited from this work by the Landis group and perhaps by the choice of a less dust-prone region on the surface of Mars (Landis [112,113,133], Jenkins et al., [122,128] and Landis and Jenkins [127,135]. Despite experiencing several dust storms, Spirit performed until March 2010, and Opportunity's solar array is still operational with a dust factor of 0.506 (that is, it is still producing about half of it capable power).[3] Relationships between dust/soiling conditions and PV performances have

[3] http://marsrovers.jpl.nasa.gov/mission/status.html.

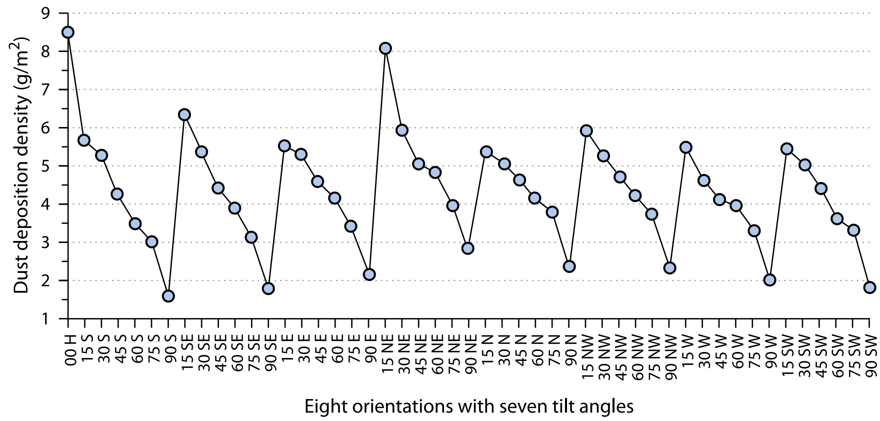


Fig. 9. Quantity of dust accumulated on glass samples installed in eight different orientations with seven tilt angles in an arid location (Elminir et al. [147]).

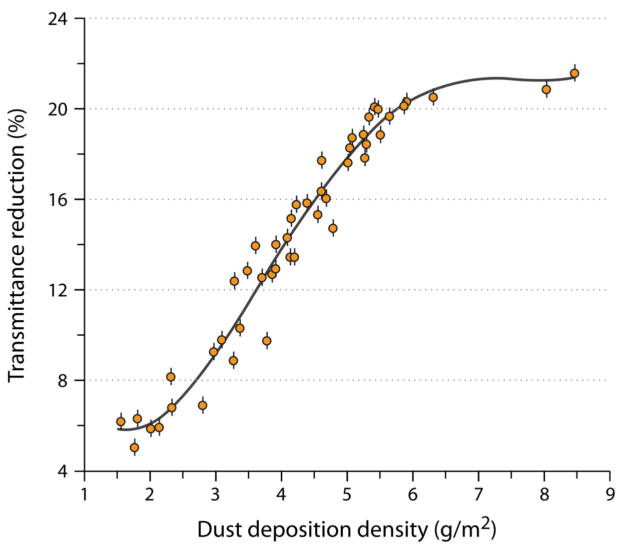


Fig. 10. Reduction in transmittance as a function of dust deposition density (Elminir et al. [147]).

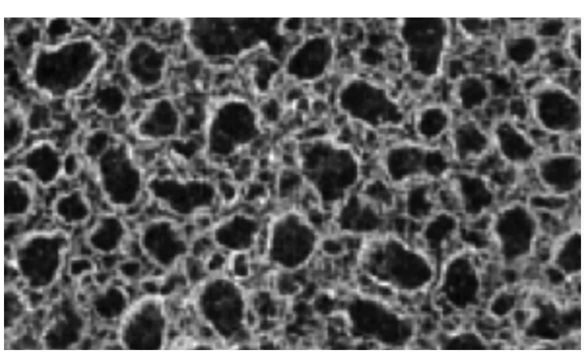


Fig. 11. Build-up of mineral deposits is visible on the surface of the glass sample (Elminir et al. [147]).

been receiving renewed attention in the recent literature [134,150,153,155,165-168,177,178,187,193,195,205,210,213]. Many of these studies complement the results already reviewed here, with added capabilities in measurement, modeling, understanding of climate sensitivity, and ability to test under extended time periods for both simulated and real conditions [129–132,137,146,156,158,181,199,207,208,212,217,222,224–228].

Table 3
Reduction in normal transmission (shown in %) as a function of various directions and tilt angles (after [147]).

Tilt angle	Orientation of glass samples							
	N	NE	E	SE	S	SW	W	NW
15°	19.71	20.89	20.52	20.17	20.28	20.17	20.02	19.69
30°	18.72	18.86	18.50	19.61	18.87	17.66	17.72	17.85
45°	16.34	18.31	15.32	15.82	15.72	15.86	14.27	16.02
60°	15.13	14.71	13.42	12.71	12.81	13.94	12.85	13.41
75°	9.67	13.97	10.24	9.73	9.25	8.82	12.37	12.51
90°	8.07	6.84	5.85	4.94	6.11	6.23	5.81	6.73

Average reduction in transmittance for glass having a tilt angle of 0° is 27.62%.

3. Dust effects on mirrors: reflectance degradation

The late 1970s saw a surge in R&D in utility-scale solar power generation in response to the world energy crisis created by the oil embargo. Concentrated solar–thermal power (CSP) came to the forefront, with the use of parabolic troughs, solar towers, and parabolic dishes to concentrate the sun's energy using reflective surfaces. These high-concentration applications were well suited to the dry, desert regions of the world where the solar spectrum was rich in its direct-normal component. Coincidentally, these regions are typically also ones that pose dust accumulation as a major concern. Even small losses in the reflection of the sunlight from these surfaces have major effects on overall system performance and viability. Thus, a small amount of dust that might be a nuisance for the situations in the previous section for PV could be catastrophic for these types of high-performance concentrating solar systems.

Among the major, early efforts in both CSP development and in dust R&D were those led by the Sandia National Laboratories in the United States in response to new federal terrestrial solar investments. Sandia launched major projects to document the impact of dust on heliostat and reflector performance—but also, to develop methods to clean these sensitive surfaces on large scales. Several extensive and useful overviews were published in this period: Berg [9,15], Blackmon and Curcija [16], Taketoni et al. [20], King and Myers [42], Pettit et al. [10, 11, 21], Call [30] and Cuddihy [39]. Some typical results for mirrors are shown in Fig. 14. Here the specular reflectance from 5 heliostats is shown as a function of mounting angle for approximately a 5-day exposure time [36]. The "face-down" configuration is shown to resist reflectance loss—though some effects are still noticeable.

From the materials science perspective, Gilligan and Brzuskiewicz [7] emphasized that one of the major design factors affecting the choice of reflectors for these concentrator applications is exactly their resistance to dirt accumulation. They elegantly

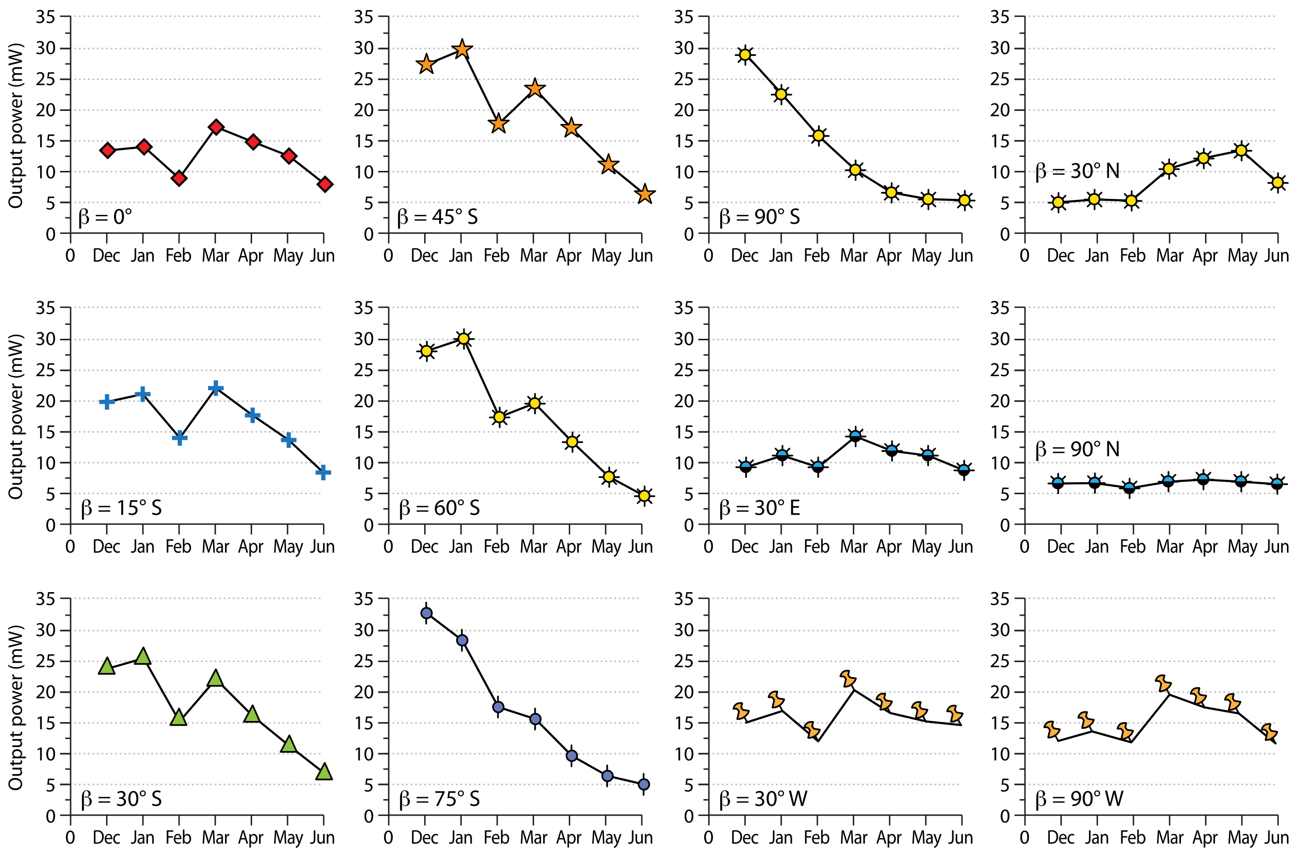


Fig. 12. Effect of the natural soil dust on the output power extracted from PV cells with different installation patterns (Elminir et al. [147]).

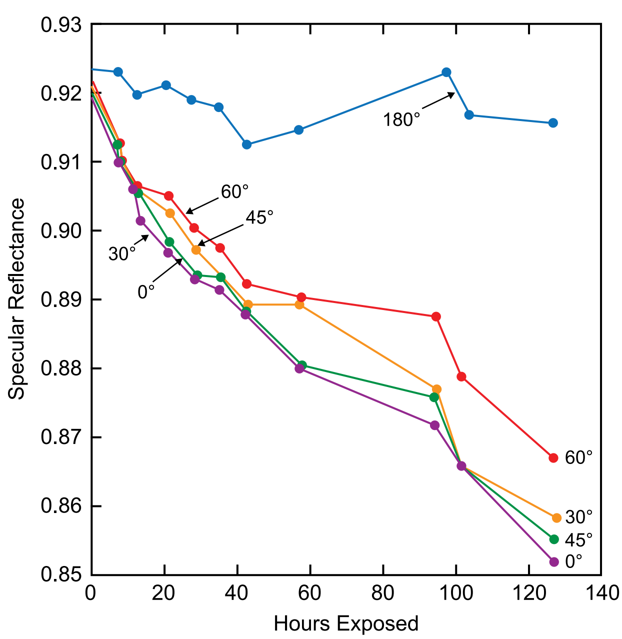


Fig. 13. Specular reflectance from 5 heliostat mirrors as a function of mounting angle (0°=face up; 180°=face down). Exposure time is ~5 days [36].

documented what might be logically inferred—that some material surfaces can accumulate negligible amounts of foreign matter, whereas others seem to attract or build up soiling that significantly reduces reflectance or transmission under the same conditions. Particles are deposited by falling onto surfaces through gravity, are attracted and held by electrostatic charges, and can be carried by wind or water droplets. After settling, particles are held by a charge double-layer, surface energy, and capillary effects, in addition to gravity and electrostatic forces. In dry conditions, the adhesion force increases rapidly in the first hour under the influence of capillary condensation at the point of contact. This water can leach chemicals out of the particles or the mirrors and/or absorb some components from the air, and it will react to form chemical and physical bonds between the surface and the particle. Berg [15] found that adhesion forces can increase to greater than 10,000 times the gravitational force, making dust removal all but impossible without damaging the surface. The optical loss caused by a particle depends on both its physical size and dielectric properties. The effect of one dust storm on two physically different reflector surfaces—glass and plastic—was described anecdotally by Blackmon and Dixon [19]. Reflectance data were taken before and after the occurrence of a major dust storm. Following the storm, a layer of fine dust was observed on all heliostat surfaces. The reflectance loss from the glass heliostat was 7.17% and that of an acrylic heliostat was 10.95%. Blackmon concluded that the difference in surfaces accounted for differences in adhesion properties. Moreover, the glass heliostat returned essentially to its pristine condition after mild cleaning with water, but the acrylic one did not. Blackmon concluded that the dirt adhesion was greater on the acrylic surface, although there was the possibility of abrasion damage or surface penetration of the particles.

Young [8] conducted a combined experimental and theoretical study to determine the effect of particle contaminant on mirror scattering properties. Experimental measurements were compared with values from the bidirectional reflectance distribution function (BRDF), which bases its values on the Mie particle-scattering theory [8,188,189]. The study involved contaminating low-scatter mirrors, characterizing the contamination level, and



Fig. 14. Sandstorms experienced in (a) Kuwait, 2011 (L.L. Kazmerski); (b) Abu Dhabi, offshore view of the city center, 2008; (c) Riyadh, Saudi Arabia, 2009; (http://worldphotocollections.blogspot.com/2009/06/sand-storm-in-saudi-arabia-and-sudan.html) and (d) Iraq, 2005 (http://www.blackfive.net/main/2005/04/sand_storm_al_a.html). The readers are also invited to recall the famous "Dubai" sandstorm in "Mission Impossible 4", or the much publicized standstorm in Abu Dhabi (http://www.greentechmedia.com/articles/read/masdar-update/).

measuring the BRDF. The mirrors were contaminated with spherical silver particles. Results were presented for particle-scattering measurements at 0.6328 and 10.6 μm. BRDF at 10.6 μm was lower than at 0.6328 μm up to about 10° from specular. From 10° to about 50°, the 10.6 μm BRDF was higher than for the 0.6328 μm BRDF. The measured BRDF data at 10.6 μm agree favorably with the theoretically predicted values for the Mie forward scattering for angular measurements between 0° and 45°. Computer computations for the forward scattering of spherical particles for various degrees of contamination at incident radiation of 5, 10, and 20 μm show that the BRDF curves decrease as the radiation wavelength increases, and that the BRDF varies with the scattering angle. Also, the scattering values do not depend on particle material and composition. The study concluded that BRDF measurements of mirrors contaminated with spherical particles agree favorably with the Mie theory prediction of forward scattering of spherical particles in free space.

Blackmon and Curcija, [16], working at two separate desert locations in California and New Mexico, made some early heliostat durability and dust-effect comparisons between the then "current-generation" second-surface silvered laminated glass and an experimental first-surface silvered glass with an experimental acrylic protective coating. They examined reflectivity degradation rates for various tracking positions and compared them with weather conditions. Time-averaged reflectivity values were determined. Losses reached 25% if some cleaning did not occur, either by nature or maintenance. Their paper provides interesting information on the beneficial effectiveness of natural cleaning by rain, snow, and frost. The following observations are based on evaluating the control of dust-related degradation of the mirror surfaces:

1. Nightly stowage positioning is extremely effective in protecting the mirrors during times when they are not in use.
2. The most effective cleaning method is washing using treated-water sprays.
3. The acrylic-protected surfaces are more difficult to clean than glass-face mirrors, even using the water sprays.
4. The dust accumulation on the acrylic surfaces is more rapid; these surfaces tend to retain the dust due to attractive forces and probably roughness.
5. The degradation rates depend very strongly on weather conditions for both glass and plastic surfaces.
6. Surfaces in the dry climate condition demand more cleaning and maintenance to avoid substantial performance losses. In the dry climate, there is no natural cleaning from precipitation.

These general observations were sometimes tempered by others [120] counter-experimental observations "requiring further investigation" of the [16] conclusions. However, these results were complemented by reports of long-term exposure tests in which the mirrors were never cleaned. For example, Freeze [18] showed a continuing and gradual decrease in the specular reflectance for silvered float glass, aluminized acrylic, and aluminized Teflon over a period of 300 days. The beneficial effects of snow, rain, and wind were indicated—but overall degradation in these mirrors was in the range of 12% to 25%, with the silvered float glass fairing best under these continuous test conditions.

Building on these results, Pettit et al. [21] determined the effects of dust buildup on specular reflectance and diffuse reflectance properties of silvered glass mirrors. They developed a characterization tool to benchmark the specular reflectance losses. Their 5-week outdoor exposure study was conducted in Albuquerque, New Mexico. The spectral reflectance losses at 500 nm ranged from 6.5% to 24% during a 39-day exposure period. The angular aperture dependence was minimal, with a maximum difference of 1.8% when varied from 3 to 15 mrad, compared to a 0.2% difference for the clean mirror. The study concluded that the main effect of dust accumulation on the specular reflectance properties of silvered glass

mirrors is to decrease the intensity of the specular beam while maintaining the same beam profile. In addition, the normalized reflectance loss values from all areas measured had the same wavelength dependence. Thus, it is possible to determine the solar-averaged reflectance loss from a *single* measurement at 500 nm—reporting a less complex methodology using their portable bidirection reflectometer. Because of similar wavelength dependence for the reflectance loss, the solar-averaged reflectance loss due to dust accumulation is equal to 0.78 ± 0.04 times the specular reflectance loss measured at 500 nm.

Two notable studies provided some early evaluations of candidate reflective materials. In the first, Rausch and Gupta [22] conducted exposure tests under concentration on aluminized fiberglass, aluminized acrylic, aluminized and silvered Teflon, aluminized and silvered glass, aluminized acrylic plexiglass, and anodized aluminum—in desert dust conditions. Their tests document as much as 2.5 years of real-time exposure, evaluating the reflectivity as a function of the exposure time and the concentration. They argued that their testing provided accelerated lifetime testing equivalent to 20 years in some cases.

The second study, by Pettit and Freese [40], examined the reflectance properties of several solar mirror materials, subjecting them to 10 months of outdoor exposures in Albuquerquenm. They showed that the primary effect of accumulated dust particles on a variety of solar mirror materials is to decrease the intensity of the specularly reflected beam while maintaining the same beam profile—validating Freese [17,18] and Pettit et al. [21]. The reduction in the specular reflectance is about five times greater than the reduction in the hemispherical reflectance, indicating that deposited particles are much more effective in scattering than absorbing solar radiation. This group also did particle analysis on the accumulated dust, and they reported that prolonged outdoor exposure increases the number of dust particles that are less than 1 μm compared to the number of particles larger than 10 μm (independent of the mirror material).

Berg [9, 15] brought the science of optics and optical properties to the study of heliostats and mirrors and their performance under soiling conditions. He reported that the optical properties of reflective optical components are most sensitive to and best described by the acceptance aperture of the collector. The higher the optical concentration, the smaller is the acceptance aperture required. For example, most flat-plate collectors have a 180° aperture, whereas central receiver systems typically have apertures of 1° or less. In this thorough analysis, he showed that the scattering effects due to dust accumulation follow Mie scattering theory, as previously reported by Young [8] and Pettit et al. [21]. The fundamentals of scattering is generally understood for surface soiling, with backward and forward components of the scattered light sensitive to the diameter and the wavelength of that light.

Wind can act as a positive or negative factor for dust accumulation. Wind can also present severe problems, as in particle damage to reflective surfaces in wind and dust storms, which can be severe in deserts (Fig. 14). Zakhidov and Ismanzhanov [37] investigated the effect of atmospheric dust particles on the reflectance of solar mirrors with front and rear reflection as a function of particle time, speed, dimensions, and angle of incidence ("attack"). In studying windstorms (i.e., dust-carrying cases), their experiments have shown that the speed of the airflow carrying the dust is the governing parameter in the destructive action of the dust particles, depending on particle dimensions. Dust particles up to ~5 μm transported by airflow of 6 m/s present no danger to mirrors. Larger particles damage mirrors at such speed. Moreover, at higher speeds (>15 m/s), particles of any dimension can damage mirrors. The caution, of course, is to avoid locations with frequent windstorms and loose soil. This is not always possible when configuring concentrating solar fields. The prevention under these circumstances is to stow the mirrors to prevent surface bombardment. (Note that this was used "semi-effectively" in the early experiences with the concentratin photovoltaics (CPV–SOLERAS (Solar Energy Research American and Saudi) program (Watkins, [29], Huraib et al. [47], Khoshaim et al. [53], Salim et al. [65], and Salim and Eugenio [68]) in Saudi Arabia in the early 1980s. However, the speed at which the CPV arrays could be stowed was sometimes too slow with respect to the advance of the sandstorm!)

Obviously, dust has equally problematic effects on CPV systems [61]. Lenses have issues relating to the glass cases discussed in the previous sections. However, CPV systems may also use reflectors. The effect of dust on the performance of such CPV systems was investigated early by El-Shobokshy et al. [57]. These highly instrumented experiments measured the dust concentration in the air continuously during the test period, as well as the rate of dust accumulation on the concentrator's surface. To allow comparison, an identical concentrator—the surface of which was kept clean—was evaluated simultaneously with the dust-soiled concentrator. The change in the reflectivity of the surfaces could not be measured simultaneously; rather, the change in the electrical output was used as the determining parameter. The change of current–voltage characteristics as a result of dust accumulation was related to the amount of dust accumulated per unit area of the collector surface (g/m^2). It was shown that for short-circuit current, cell temperature (by as much as one-third in these desert climates), and efficiency, major reductions occur immediately as the dust starts to deposit onto the collector surface; but the rate of decrease is slower for dust accumulations beyond a "2 g/m^2" level. These *I–V* characteristics are presented in Fig. 15. El-Shobokshy, Hussein [80] proposed that the dust accumulation per unit area is "the" representative parameter, rather than the exposure time for such studies. Similar data have been reported recently by Sulaiman et al. [194] and Zorrilla-Casanova et al. [198]. El-Shobokshy and Hussein [79] also determined the dependence between dust accumulation and average cell temperature: higher accumulation shades cells and lowers the temperature. Although interrelated, the exposure time depends on climatic conditions—and for cleaning schedules, the measurement of the dust build-up (density or thickness) would be the better indicator, for example.

Instrumentation to help R&D with controlled laboratory conditions began to be developed in the early 1980s. Collier [41] designed and used a "dust-storm simulation chamber" to evaluate

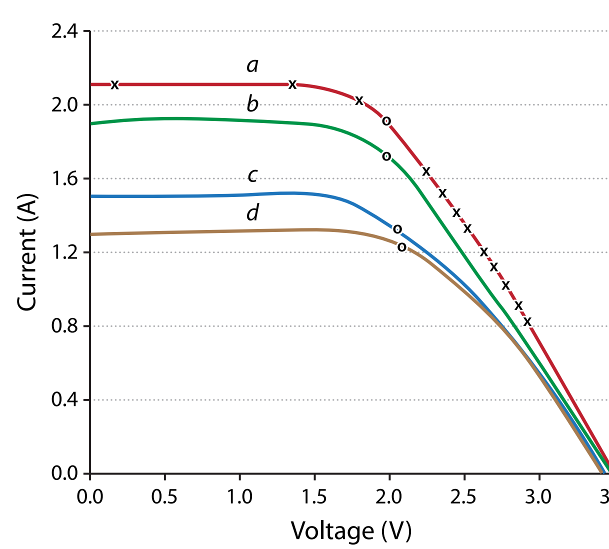


Fig. 15. Current–voltage characteristics of CPV module with various levels of dust accumulation: (a) clean glass surface; (b) 0.85 g/cm^2 dust; (c) 1.85 g/cm^2 dust; and (d) 5.4 g/cm^2 dust. After El-Shobokshy et al. [57].

solar concentrator degradation, specifically to characterize the loss in reflectivity. The dust-storm simulator was further improved by the Texas Tech efforts by Bethea et al. [44,50], Randall and Morris [45], Cooper [55], and Bethea [58] to improve and enhance the capabilities for controlled experimentation for mirror-dust evaluation. These chambers and programs enabled researchers to develop:

- Procedures for simulating long-term exposure of mirrors to dust storms under controlled and predicted conditions (no waiting for dust storms!) to assess the effects on mirror quality as indicated by reflectivity.
- An economically and technically practical method to test the cleaning of the mirror panels in use at the site—in this case, the Crosbyton Solar Power Project (CROSPO) test site.

These controlled experiments provided in-depth modeling with predictive equations for the loss in reflectivity with exposure time. Defining the amount or percentage of degradation (L) as $L=R_L/R_o$, where R_L is the loss in reflectivity and R_o is the initial reflectivity. Bethea et al. [50] related these values to the fundamental parameters for their wind-dust experiments, and after some complex integral calculations, they found a simple expression: $L=A+E\sigma v+F\sigma v^2$, where A, E, and F are coefficients that are calculated from the chamber experimental conditions, σ is the total mass of the dust (per unit area), and v is the time-weighted average velocity of the dust particles.

Test samples of various mirror materials were quantitatively and qualitatively assessed by reflectivity measurements to validate this relationship. These chamber experiments and the modeling were then used to predict with fair accuracy the real-world conditions for reflectivity losses due to dust storm effects (at the test field at Texas Tech's Crosbyton Solar Power Project test site). These results provided the first real validation that complex processes, such as dust storm effects on mirror reflectivity changes, could be modeled accurately. Moreover, the use of simulators to control the conditions and accelerate the times was shown to be foundational to this modeling effort.

Research in the late 1980s and early 1990s returned to a focus on materials development for minimizing soiling on mirrors and reflectors. Orlov et al. [66] investigated the dynamics of soiling of two kinds of solar-concentrator configurations and designs: (1) glass with back reflection and (2) a reflector on a base of polyurethane foam. Exposures were carried out during the dry season and during the period with precipitation. The spectral composition of light reflected from dusty and clean facets was investigated and showed that dust density weakens the light intensity in the visible part of the reflected light's spectrum, which is important for wavelength-selective receivers. The reflection loss was correlated with the soiling time, as tested in the then state-of-the art solar furnace facility in Tashkent, Uzbekistan.

Khrustalev and Ragimov [72] collected experimental data on the bidirectional and directional hemispheric reflectivities of solar reflectors (mirrors) soiled in the process of operation by dust deposits. The investigation established a basis to account for scattering of radiation by dust-deposited mirrors, with these formulations suitable for performance calculations and predictions.

The Negev desert in Israel is a region with outstanding solar resources, but the very dry and dust-prone area presents some issues for solar deployment. The Ben-Gurion Solar Energy Center has taken advantage of these conditions to try to mitigate the problems associated with the dry deposition of airborne dust, and these programs have provided valuable information for others working in similar conditions. Biryukov [100,101], as part of the program to protect the reflective solar surface, initiated some comprehensive materials research projects. These have used the angular dependence of the dry dust deposition rate, separating the diffusive (isotropic) and vertical components. The experiments examined the dust that was naturally collected on flat glass reflectors mounted on a specially prepared wind vane that allowed the exposure angle (slope of the samples) to be varied. The collected particles were painstakingly counted and sized by means of a computerized optical microscope. The angular dependence of deposition rates for several groups of sand particle sizes were then extracted from these measurements. Several key observations were made: (1) No deviation was found from the expected cosine-type angular dependence (i.e., the dust-coating thickness varies with the cosine of the incident deposition angle [229]). This result was interpreted as domination of vertically directed particle flux over diffusive components in the vicinity of the collecting surface; (2) This conclusion was compared to the results of existing dry-deposition models and showed excellent correlation; and (3) Size distributions of particles collected on the flat horizontal surface were converted to a volume mass concentration. The integrated value of this concentration (0.3 μg/L) supports the data on deposition velocities for the coarse particle mode and low-wind speed, published by Lin et al. (1994).

Offer and Zangvil [107] added to these results with further measurements of airborne particle concentrations and their accumulation on solar mirrors at this same site. These measurements were during periods of relatively isentropic conditions (from 7 h to 7 days) and included periods during prolonged dust storms (up to 6 h). During these isentropic periods, airborne particle concentrations ranged between 75 and 156 mg/m^3, the amount accumulated on the reflector surfaces varied between 511 and 832 mg/m^3, and accumulation ranged between 0.17 and 0.20 g/m^2. Typically, the reflectivity decreased by 4.2% to 5.1%. During a more severe nocturnal dust storm, airborne particle concentration reached 540 mg/m^3, with the associated dust accumulation of 0.13 g/m^2 (average) and a decrease in reflectivity of 1.8%. Such significant dust conditions result in significant losses to the reflectivity and operation of the solar concentrator, and Offer and Zangvil concluded that developing mitigation methods was mandatory.

Berg [9] surveyed mirror-dust interactions and experiments and proposed various techniques that could modify these interactions to affect cleaning. He concluded that the dust accumulation is the result of multiple forces. Some of these forces may be adaptable to dust removal, and these include surface energy modification, control of surface roughness, use of special electronic properties, control of residence time, electrical charging, and surface accelerations. The usefulness of these ideas depends on developing a better understanding of the interaction of the forces, and on experiments now under way to test them on real surfaces and systems. However, all of these ideas have been put to practice for some degree of successful dust mitigation.

Biryukov [118,119,123] extended the "flat reflector" work with investigations of degradation of reflectivity of parabolic mirrors due to dust. Three different techniques for measuring dust influence on specular properties of parabolic concentrator were performed using an individual mirror panel of a large parabolic dish. Direct measurements of the intensity of concentrated light confirmed the results of measurements with a specular reflectometer. Both measurements were consistent with the measured particle size distributions on the surfaces determined by a computerized optical microscope.

Badran [139] reported an interesting application that is not directly solar, but one that is certainly sensitive to dust and that provided some useful data for solar installations. He studied the factors limiting the performance and requiring maintenance of the Cherenkov telescope at the Fred Lawrence Whipple Observatory, Mt. Hopkins,

Arizona.[4] In this work, test mirrors were installed at the two potential sites for the telescope installation, one at 1300 m and the other at 2300 m above sea level on Mt. Hopkins. After an exposure of more than two and half years in the open air and a schedule of monthly cleaning by water, the mirrors did not exhibit any adverse degradation in their reflectivity. The only reflectivity change (about 5%) was at a wavelength of 310 nm. The results at both sites were comparable. Sunlight exposure was reported to be the main parameter leading to mirror degradation, although there was some speculation that "contaminants in the influence of the sunlight" could be involved. A variety of cleaning methods were employed, but all provided the same reflectivity restoration—with somewhat marginally better performance for mirrors at the 1300 m location. The results suggested that mirror cleaning can minimize the downtime for what might otherwise be required to re-coat damaged surfaces. Contamination was a controlling factor in developing the atmospheric Cherenkov telescope, and this study was crucial in identifying and minimizing any such degradation due to soiling sources. The development of the baseline of the mirror-cleaning program was mainly driven by the "science" requirements for reflectivity. Dust at Mt. Hopkins was the major contamination source for the telescope optics, with the major effect being the loss of the blue portion of the light spectrum. The results of the long-term experiment show the possibility that the reflector can be maintained at an acceptable level. Monthly water washing proved to be able to prevent the accumulation of the dust particles and keep the mirror in good conditions. (Note that covering the mirrors did not prove to be effective in reducing dust exposure; for this reason, dust covers were not built for the much larger VERITAS telescopes.[5]) Within two years and eight months, the coating, with cleaning, exhibited an expected 5%–7% drop in reflectivity at 310 nm and no significant decrease at other wavelengths—similar to the test-mirror measurements. This compares with a decrease of over 20% of the mirrors exposed for 3 years without cleaning. Water washing was concluded to be the most effective mechanism to preserve the reflectivity of the 10-m-diameter mirrors, although alternative dust prevention methods are being monitored and pursued as less labor and resource intensive alternatives.

The commercialization and huge growth of the solar industry has provided a focus for eliminating issues such as "dust" for the performance of solar installations. These installations have now passed the 100 GW level worldwide. Spain has become a major market for solar installations, with more than 4 GW of installed capacity at the end of 2010—about 3.4 GW in PV and 0.6 GW CSP [230]. This focus on eliminating dust issues is especially important for using and validating CSP approaches. A 5% loss in reflectivity of the mirrors and heliostats for a CSP solar field is potentially more critical than a 5% loss in transmission of a PV glass superstrate.

Fernández-Reche [149] reports on the statistical analysis of reflectance measurements taken in a heliostat field at the Plataforma Solar de Almería [6] for a central solar tower system using 93 heliostats. This study sought to simplify and lower the time and cost investments. He conducted a statistical study, measuring only 12 of the 1116 facets—with each heliostat having twelve 3.3-m^2 facets, for a total reflective surface of 39.6 m^2. The statistical error associated with this mean reflectance was determined to be less than 0.3%. These results were validated with the Fiat-Lux heliostat field simulation code [121], using the mean field reflectance found by the method described here as input; there was excellent agreement between measured and simulated incident solar power. From both an economic and operating perspective, the results obtained provide substantial savings, especially for any heliostat field with more than 100 units. The methodology described can be used in other solar–thermal systems (e.g., parabolic trough collectors or dishes, with minor modifications and details for the specific conditions of each of the systems studied). Some sources of error were identified in the statistical analysis associated with the replacement and condition of the heliostats in this particular study. Recently, Ajadi et al. examined these same effects on simple solar thermal dryers [161].

Much of the work of examining mirror degradation due to dust is incorporated synergistically in studies of cleaning techniques discussed in the next section. In summary, dust accumulation reduces spectral reflectance at every wavelength and induces diffuse reflectance, which can be as detrimental for solar concentrators as a reduction in spectral intensity. Table 1 also provides a chronological summary of the major investigations and reports for concentrators and reflective optics.

4. Dust particle physics and chemistry

The nature of soiling varies from location to location throughout the world. Urban areas in a northern climate might be expected to have soiling dominated by pollutants found in those environments (e.g., airborne particles from coal-fired utility plants, vehicle emissions, particulates from construction). Likewise, agrarian locations might find species from fertilizers, windblown soil, or plant matter. In the dust studies by Cabanillas and Munguía [195], a group of experts identified the major sources of the dust collected from their glass surfaces in Mexico to be clay, sand, soot, mushrooms, spores, and vegetable fibers. Organic material found in the urban and agricultural areas provide the "glue" that contributes to holding the dust to the surface, as well as holding dust particles together. The report of the chemistry and makeup of dust from the desert regions of the world should be expected to be significantly different, dominated by quartz, feldspar and other sand components [3]. This section discusses some aspects of the dust particle physics, morphology, chemistry, and composition, focusing on dust from the world's arid areas (e.g., Middle East and Northern Africa [MENA][7] regions and India), where there is growing interest in solar technologies and where dust issues threaten to be showstoppers for widespread solar-technology operation and adoption.

4.1. Particle size and morphology

A research interest from the earliest soiling investigations has been the physical properties (size and geometry) of the dust that settles on solar surfaces [76]. Optical microscope observations of the 1970s led to the definition held ever since that particle sizes were "less than 500-μm diameter." The first investigations used particle scattering theory [8] and sought to establish relationships between the dust element size and the light scattering and resulting light transmission. Young measured and used the bidirection reflectance distribution function to compare experimental measurements to this analysis. Similarly, Al-Hasan [114] used mathematical scattering theory treatment (assuming that dust particles were equally sized and spherical) to formulate relationships relating the normal and diffused incident angles to the beam transmittance; he developed a general relationship for direct-beam radiation received by the tilted surfaces that he was concerned with. These derived formulations can accurately predict the observed experimental results. Ju and Fu [200] have also modeled the particle size effects

[4] www.sao.arizona.edu/FLWO/whipple.html.
[5] http://veritas.sao.arizona.edu/.
[6] http://www.psa.es/webeng/index.php.
[7] http://web.worldbank.org/wbsite/external/countries/menaext/0,menuPK:247619~pagePK:146748~piPK:146812~theSitePK:256299,00.html.

on light transmission, packing densities, and forces holding the particles to the surface. Table 4 summarizes the particle sizes, distributions, and effects on optical and performance parameters that have been examined in some detail by investigators over the past decades. The particle sizes and morphology have been determined using both optical techniques (including commercial particle analyzers), scanning electron microscopy (SEM), and recently, scanning probe microscopies.

A good example is that of Biryukov [98,99,118], who provided particle analysis for understanding dust problems. These important studies involved evaluating particle-size distributions using various microscopy techniques. Relationships were established between deposition rates, tilt angles, and performance and dust particle size. Fig. 16 provides an example in which the deposition rate of dust on a solar tracking mirror is shown as a function of particle size. These particle-size studies conducted in regions of the Negev desert found that 90% of the dust particle diameters could be sized between 5 and 60 μm. These relationships help understand the physical mechanisms that cause adhesion and retention of dust particles, which, in turn, can lead to potential techniques for mitigation.

4.2. Dust particle composition and chemistry

Table 4 also includes contributions that have examined the material and chemical makeup of dust from various parts of the world. As already noted, the compositions reflect the environments of the regions where the dust originates. This section looks in more detail at the "MENA" dust, with data that have been gathered from these desert and sand-dominated countries.

Elminir et al. [147] conducted extensive mineralogical analysis using X-ray diffraction (XRD) to identify the chemical composition of the deposited layers. The elemental concentration and characteristics could be used to study the nature of the main emission sources. The dust particles were mostly composed of quartz and calcite, with smaller amounts of dolomite and clay minerals. Fig. 17 presents the results of the XRD analysis. The major constituents were silicon from desert sand (quartz, or silicon dioxide, SiO_2) and calcium from the mineral calcite (calcium carbonate, $CaCO_3$); minor constituents consisted of aluminum, iron, magnesium, potassium, and sodium. Other elements such as sulfur, vanadium, nickel, copper, zinc, and arsenic were attributed to "local emission sources," but were not further measured or specified.

Analyses of dust sand collected from module surfaces in the United States and the MENA regions (Table 5) show that the major components are quartz silicates (SiO_2), about 75%; and feldspars ($NaAlSi_3O_8$, $CaAlSi_3O_8$, $KAlSi_3O_8$), about 20%. Elminir et al. [147] provided extensive energy-dispersive spectroscopy (EDS) analyses of dust from module and glass surfaces in Helwan, Egypt. These data show the presence of the expected silicates and feldspars—but also, the environmental effluents from the cement industry in this region near Cairo. The authors' measurements of samples of dust obtained from this same general location complement the reports from Elminir (see also Fig. 2). Samples for other regions (e.g., Upper Egypt, Libya, Saudi Arabia, Oman, and Bahrain) do not have these cement components, but do have elevated levels of Na and Cl because these samples were obtained from areas near the Mediterranean Sea or Persian Gulf. The samples from Iraq were from the Bagdad airport region, and they likely show the influence of both the airport and military traffic (and perhaps the military actions in this part of the world).

These data show that even in one portion of the globe, the composition of the dust can vary significantly because of the environment. Additionally, the particle size and morphology of the sand can vary from region to region, as highlighted in some examples in Fig. 18. The distribution of particle sizes may be either uniform or bimodal (Fig. 18a and b), and particle morphology may also vary, from rounded to rough (Fig. 18c and d); compared with sands reported by Bouaouadja et al. [125]. This morphology can greatly influence the interaction with particular surfaces and the forces encountered in capturing or holding that dust on contact [171].

The physical deposition and deposition rates depend on the metrological conditions, particle size, and periodic dust accumulation rates. This has been observed in many studies, and reported recently by Mohamed and Hasan [223] for various times in the Libyan Desert. Fig. 19 shows their report of the reliable distribution of particle numbers (i.e., volume) as a function of the particle diameter for various periods. They showed that dust particles have distinct transmittance indices (ranging from opaque to almost transparent)—and the density depends critically on the type (clay, sand, organics) and the season of the year. The relative performance (power) for representative modules over this period (cleaned and uncleaned conditions) is presented in Figs. 20 and 21. They did report that as little as 10% shading from the dust results in more than 50% loss in power. This relationship between the dust physical nature and the transmittance through the glass is further evidenced by the recent report by Aassem et al. [221]. They showed the anticipated decrease in the transmittance on the dust density, along with the wavelength response. In their study, wavelengths above 570 nm, the variation between the density-transmittance characteristics with respect to the average was ~2.5%. For wavelengths less than 570 nm, it was measured to be about 11%. Dust effects are more significant (detrimental) at lower light wavelengths. They also modeled this behavior to provide verification to their data.

4.3. Dust: airborne, deposited, and deposition processes

The understanding and eventual control of dust on solar and other surfaces eventually will significantly depend on the understanding of the mechanics of the fundamental dust accumulation process (dust deposition). The soiling or deposition process itself involves (1) the process of delivering the dust to the surface (directive or attractive); (2) the initial adhesion; (3) changes in the adhesion (condensation and chemical reactions that can occur); (4) alterations in the surface (weathering, contaminant accumulation); and (4) restorative processes (cleaning by rain or snow, or maintenance). These processes themselves involve multiple and sometimes interdependent interactions that add layers of complexity to modeling or unraveling the controlling parameters. For example, the initial adhesion depends on the surface itself, its composition, chemistry, morphology (smoothness, roughness), conductivity, charge, orientation, optical properties, hardness/softness, temperature, mechanical motion, and even down to micro- or nano-characteristics.

4.3.1. Aerodynamic behavior and accumulation relationships

One area that can be fundamental is the relationship between the ambient dust conditions to what is actually accumulated or deposited. From other studied area, it is known that the constituent airborne constituents are different to what might settle out on a given surface [75,116,155,163,188]. This includes various geological studies, concerns about the conditions following September 11, 2001, general health issues, certain industries such as mining, and building maintenance and contamination control [231–233]. Recently, control of soil accumulation on roofing materials has become a major issue relating to energy efficiency and sustainability ("keeping those white roofs reflective"). The physical characteristics of aerosols have been

Table 4
Results of selected investigations of the physical and chemical properties of dust.

Investigators [Location]	Size/Distribution	Size/Morphology	Chemistry/Composition	Comments
Young [8]	Modeling of dust grain size effects on light transmission			Derived bidirectional reflectance distribution function (BRDF) to compare experiment to model
Roth & Anaya [35] [New Mexico, USA]	Particle size distributions (*determined using computerized image analyzer*)	SEM images of particles (morphology rounded, typical of fly ash)		(Mirrors) Outdoor testing for naturally cleaned (wind/rain) and uncleaned; mirrors with only natural soiling have great concentration of particles $>10\ \mu m$ (particles of $\sim 2\ \mu m$ largest population); differences in particle sizes for day and night exposure
Brem et al. [43] [Daggett, CA USA]		SEM and optical microscope images (quartz grains with smaller clay and salt deposits observed on grains)	EDAX concluded silicates (quartz, feldspars) dominated, followed by non-silicates (muscovite, biotite, chlorite, clay, etc.)	1–5 μm range particle diameters; tabulated compositions of particles (34%–76% quartz) and 24%–17% feldspar)
Roth and Pettit [36] [New Mexico, USA]	Particle size distributions; particle sizes determined by commercial "particle sizer" (optical technique)			Small particles (0.3–1 μm radius) most significant source of light scattering; the longer exposure, the concentration for particles $<5\ \mu m$ increases
Morris [32] [New Mexico, USA and Daggett CA]		SEM analysis of grain morphology for CA and NM locations	X-ray diffraction (quartz, feldspar, calcite, micas, gypsum, kaolinite); SEM analysis of grain morphology	Particle sizes typically <2-μm diameter; results similar to Woyski above (e.g., salt and mica deposits on quartz grains); Analysis for both NM- and CA-site particles, which differ significantly
Berhea et al. [44] [West Texas]		SEM images of damaged glass and organic surfaces (not particles themselves)		Carolina mirror had best abrasion resistance (compared to acrylics, plexiglass, alzak, etc.)
Roth [48]	Number and size distributions; commercial "particle sizer" (optical); used SEM to determine particles 0.1 to 1 μm (out of range of the commercial particle sizer)			Modeled scattering process for grain sizes; bimodal particle distribution, with one peak (highest) 0.075–0.10 μm and second peak in range of about 2–8 μm (radius) (higher radii particles fall off exponentially in distribution)
Sayigh et al. [56] [Kuwait]		SEM analysis of morphology (generally very rough grains)		(Glass) Dry dust analysis (sand)
Khrustalev and Ragimov [72] [Crimea]	Particle distributions and particle sizes (particle counter over defined region)			Report numbers of grains with a given diameter. Tabulated data indicate a bimodal distribution (near 0.4 μm and 1.5–2.0 μm)
El-Shobokshy and Hussein [79] [Riyadh, Saudi Arabia]	Used laboratory-composed dust (limestone, cement, and carbon) with mean diameters of 50–80 μm, 10 μm, and 5 μm, respectively			(Glass–PV) Conclusion included importance of including mean diameter and standard deviation in reporting size distributions.
Biryukov [98,99] [Sede Boqer, Israel]	Concentration (mg/m^3) determined as a function of dust particle size; deposition rate as function of particle size; percent of area covered as function of particle size			(Glass Mirror) Perhaps a bimodal distribution is present (except for the percent-of-area data)
Biryokov [115] [Sede Boqer, Israel]	Number of particles vs. particle size; deposition rate vs. particle size; mass concentrations vs. particle size (Fig. 7)			(Mirrors) Determined a coefficient of attachment from data (results similar to previous Biryukov reports); cosine dependences of deposition of dust
Al-Hasan [114] [Kuwait]	Modeling of light scattering as function of dust particle size			Validation of model with experimental results
Biryukov et al. [115,119] [Sede Boqer, Israel]	Report of number of particles as function of their diameters. Particle size determined by computerized optical microscope			Peaks at 20 μm (corrected to 10 μm empirically)
Bouaouadja et al. [125] [Algeria]		Optical microscopy of sand particles		Particles have irregular shapes

Goossens [143] [Belgium]	Determined mass percentage as function of grain diameter; measured shape factors (rounding) as function of grain diameters; modeled dust deposition flux as function of grain size			Peak at about 40 μm for mass percentage; rounding due to wind
Elminir et al. [147] [Helwan, Egypt]			X-ray diffraction analysis (Si dominates, with Al, Fe, Mg, Cl). This is a very extensive analysis of the compositions; *also, see theses by* Hassan [97] *and* Elbied [104]	(Glass–PV) Analysis of dust particles for this location in Egypt shows the effect of effluents from the cement factories in the dust-deposited on the PV modules
Ju and Fu [200]	Modeling of dust particle size and effect on light transmission			Wavelength dependence. Shows directly dependence on grain sizes; elementary modeling, similar to that of Young [8]
Cabanillas and Munguía [196] [Sonora, Mexico]	Dust particle distributions (using commercial particle size analyzer, based on laser diffraction technology)	Optical micrographs showing highly irregular grains, as well as distribution of spherical ones	Composition (in order of dominance): clay, sand, soot, mushrooms, spores, and vegetable fibers (agricultural region of Mexico)	Number (frequency) vs. particle size with peak at about 0.8 μm; bimodal distribution for surface area % vs. particle size (1 and 20 μm); and volume % vs. particle size with peak at 20 μm (no particles greater than 400 μm were found)

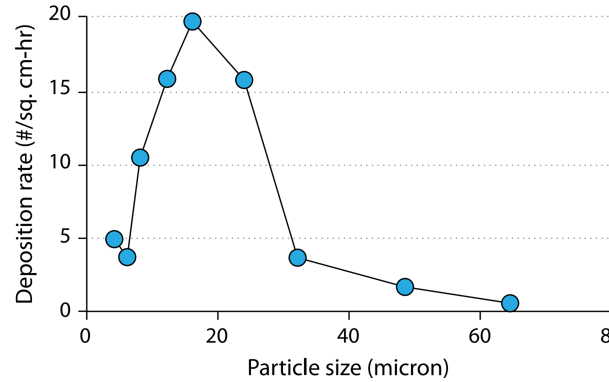


Fig. 16. Solar tracking mirror with deposition rates according to particle sizes (Biryukov, [98]).

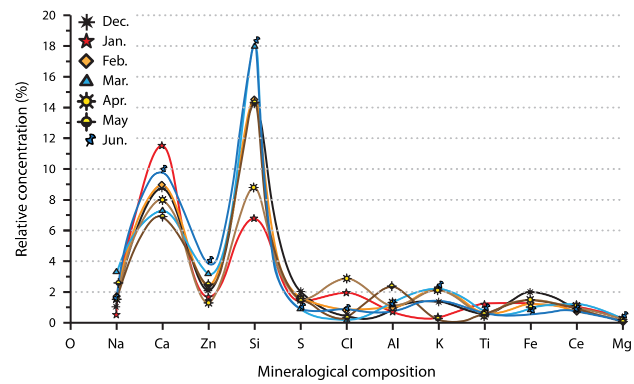


Fig. 17. X-ray diffraction analysis of the polluting (soiling) material, showing the most important organic components (Elminir et al. [147]).

intensively investigated using an arsenal of characterization methodologies [233,234][8].

The aerodynamic behavior of airborne dust particles is a function of several key parameters. The larger diameter particles are primarily impacted by gravitational and inertial effects, while the smaller particles interact largely to inter-particle forces. These airborne dust influences are [231]:

4.3.1.1. Gravitational settlement. The particle falling rate through air depends upon its diameter, density, and the shape. Much this motion of the particle has been modeled as a equivalent geometric sphere, which has the forces of its weight, the drag, and the up thrust.

4.3.1.2. Brownian motion. This applies to very small particles primarily, the case in which the forces are no longer balanced on all sides, resulting in the particles undergoing random and irregular movements. This movement is modeled on the statistics of the complete set of particles—quantifying the Brownian motion in terms of mean-square displacements.

4.3.1.3. Eddy diffusion. Dust particles are also under the influence of turbulent airflow. The flux of these particles to the laminar region near a surface give the particles a high probability of being deposited on that surface. The eddy actin imparts sufficient inertia to a dust particle to bring it into the laminar region—where there are no forces (except Brownian motion) to take it away from the surface—and the Brownian gradient is only to the surface (deposition).

[8] www.parrett.uk.com/dustmeas1.htm.

Table 5
Dust analysis from PV or other solar surfaces in the MENA countries for major elemental components from Elminir et al. [147] and from the authors. Measurements are EDS (with the oxygen concentrations estimated from complementary X-ray photoelectron spectroscopy (XPS). The range in the Elminir data is due to seasonal changes determined in the collected dust from the surfaces (see Fig. 2). Major "cement" components are indicated by the shaded rows. (*ND*=not detected).

Species	Countries (relative concentrations %)							
	Libya	Egypt			Saudi Arabia	Oman	Bahrain	Iraq
		Elminir (Helwan)	(Helwan)	(Toshka)				
B	ND	ND	ND	ND	ND	ND	ND	ND
C	0.8	–	1.1	0.2	0.8	0.5	0.1	1.6
O	(46.6)	–	(43.2)	(47.6)	(46.8)	(46.4)	(47.4)	(44.3)
Na	4.9	0.3–3.2	2.7	< 0.03	3.4	4.3	5.2	1.0
Mg	1.9	0–0.02	1.1	2.2	2.0	1.2	1.1	1.7
Al	0.2	0.07–2.9	3.2	0.1	0.2	0.2	0.1	0.4
Si	26.7	6.6–(27.5)	25.2	28.6	28.7	29.7	28.4	26.4
P	ND	ND	ND	ND	ND	ND	ND	ND
S	0.4	0.9–1.9	1.1	–	1.3	–	–	0.5
Cl	3.3	0.02–2.1	1.8	0.07	2.1	3.9	4.3	0.6
K	1.9	0.01–2.3	2.2	1.4	1.5	2.1	2.0	1.6
Ca	1.7	6.7–11.2	12.7	2.4	2.0	2.6	2.5	2.6
Ti	–	0.08–1.0	1.0	–	–	–	–	< 0.1(?)
Cr	–	ND	0.4	–	–	–	–	< 0.1(?)
Mn	–	ND	ND	0.04	–	–	–	0.06
Fe	–	1.1–2.1	3.1	–	–	–	–	0.5
Zn	–	1.2–3.8	2.7	–	–	–	–	0.3

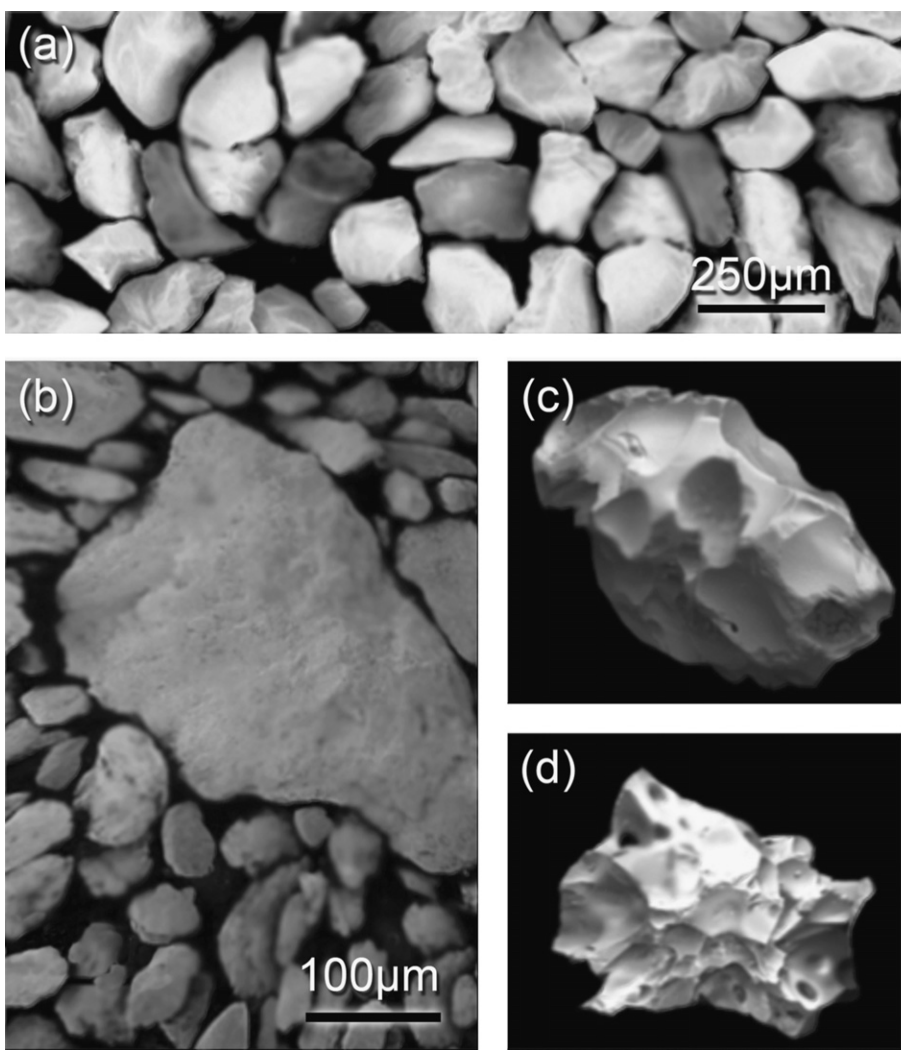


Fig. 18. Comparisons of size and morphologies of sand particles removed from PV module surface from (a) Libya (~120 μm average diameter with fairly uniform distribution); (b) Iraq (with a bimodal distribution (~400 μm and ~80 μm). Single grains are shown in SEM images: (c) Libya with rounded features, likely from wind action; and (d) Oman with rougher morphology. Both these sand particles are about 120 μm in diameter.

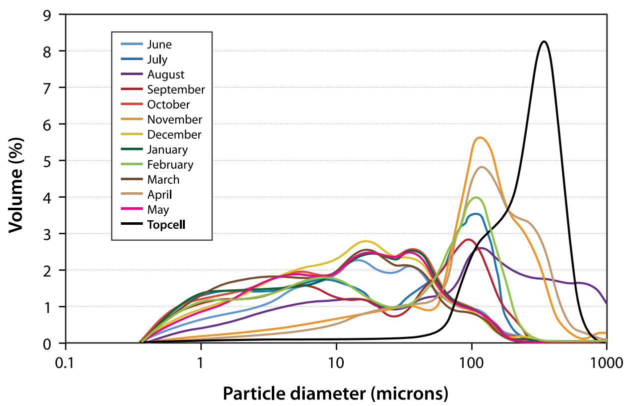


Fig. 19. Dust deposition in the Libyan Sahara Desert showing volume density as a function of the particle diameter for various monthly periods (Mohamed and Hasan [223]).

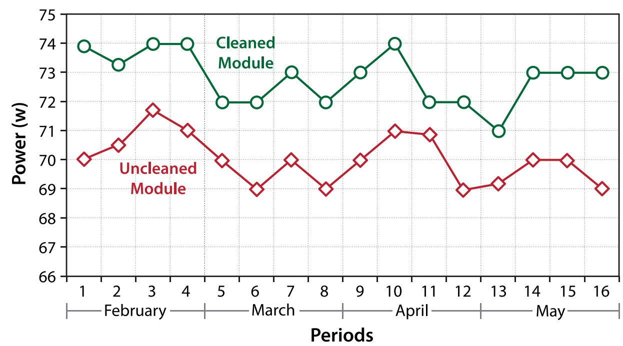


Fig. 20. Performance differences between cleaned and uncleaned (dust accumulated) PV modules over the periods in Fig. 18 (Mohamed and Hasan [223]).

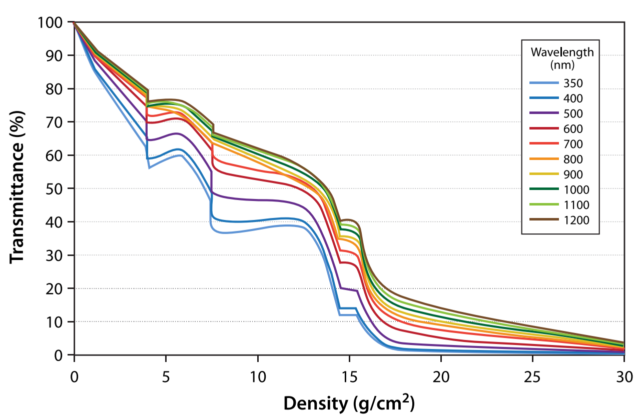


Fig. 21. Measured variation of dust density with transmittance through the glass at various wavelengths (Qassem et al. [218]).

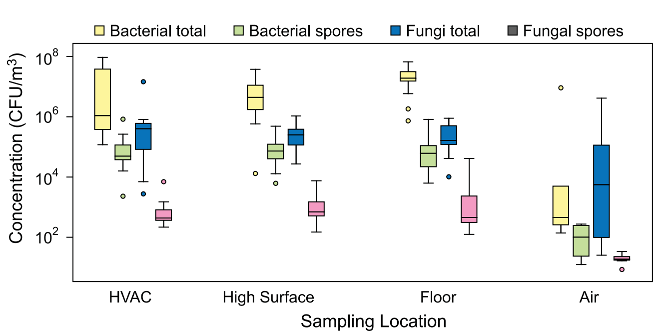


Fig. 22. Comparisons of concentrations of samples from various locations to the airborne components [235].

4.3.1.4. Electrical charge and states. Dust particles can gain charge in a number of ways, including gaining induced charge in movement. Uncharged particles can have dipoles induced due to Van de Waal's forces. These electrostatic forces can increase the rates of coalescence. Of course, if the charge is opposite to the surface, the particle can be bound to that layer. Highly conductive surfaces help prevent this effect (which is one that is relied upon in paints or power sprays that need such attachments).

4.3.1.5. Coalescence. In these situations with concentrations of airborne dust particles, the collisions between the particles—and in turn, these can cause the particles to coalesce (sometimes termed coagulation) to form larger particles. As the process continues, some particles will grow to the extent that their terminal velocity becomes so significant that they fall out of suspension. These particles can have irregular charge distributions, morphologies and irregular shapes, and more influenced by micro-pressure regions—all potentially making the probability of adsorption at the surface much higher.

4.3.1.6. Impingement and re-entrainment. Excessive velocity and excessive turbulence cause the dust particles to not follow the streamlines—and impinge on the surfaces. This can occur at all angles—causing deposition by impact of the particles with the surfaces. Chaotic turbulence can cause re-entrainment—in which a particle on the surface (within the laminar region) can be made to roll over the surface by viscous drag of the air. This action may cause the particle to "bounce" until it momentarily escapes the sublayer—and it reenters the airstream. Thus the airborne population can change due to the surfaces it encounters as well.

4.3.2. Airborne and deposited dust differences

The differences in species between the dust-deposited on the surface of a solar collector and what is present in the airborne constituents are related, not usually identical, and the relationships are not well documented [75,83,103,171]. Some are due to the behaviors discussed in the previous section. The complete understanding and the subsequent modeling is not well developed—and is an area that could be transformational for the dust mitigation solutions. These measurements could lead to the development of useful predictive models.

Building and health-safety studies have many examples showing the differences between airborne components and the concentrations samples from various surfaces one illustrative example is shown in Fig. 22, which presents microbial concentrations characterized from various sampling locations. A wide range of concentration data from difference sites is measured—but no correlations were made to the host airborne concentration samples. At first glance, it would appear that little connection seems to exist, but the authors did not the differences in air flow and surface composition would be the major sources for the differences.

The understanding of what is present in the airborne components and what gets deposited on the solar collectors is one area that needs further research and development. Additionally, the local conditions (wind velocity, temperature, humidity, turbidity, structures and orientations, vegetation, …) are as important and the inherent collector properties (materials, coatings, tilt, …) for fully addressing and solving these dust issues.

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5. Mitigation: approaches to remove or prevent dust accumulations

Dust is not a major concern in areas that have low-soiling conditions and/or periodic precipitation that cleans the surfaces naturally. This is the case in most of the United States and Europe. Mani and Pillai [184] may be consulted for detailed descriptions of the various climatic zones and the dust-concern level, and recommended cleaning and mitigation approaches based on the zones. In some situations, nature can be the most effective and least costly cleaning agent for the dust problems. The natural effect of cleaning by rain or snow has been observed in numerous studies throughout the world. In most cases, rain washes away dust and soiling, and collector performances are usually restored to nearly original capacities. Fig. 20 shows the reflectance for a long-term exposure test (480 days) conducted by Roth and Pettit [36]. (See also Fig. 2 for complementary recent data in several world locations.) In Fig. 23, each peak and trough represents the natural oscillation between soiling and cleaning. Daily degradation from soiling was as much as 14% when light rains were followed by high winds and dust storms; also, reflectance increases were seen to be more than 12% after heavier rains or snow.

Rain, additional moisture, and especially heavy morning dews are *not* the panacea for dust mitigation. In fact, rain can compound the dust problem if the duration is brief and intensity is light. In light rains, the rain droplets can collect airborne particulate matter and deposit high concentrations of residue when striking the surface of a collector. If the rain does not persist to wash off this residue, then—when dried—large dirt spots will populate the surface. Cuddihy [39,51,54] described deposition and soiling mechanics that he used to develop an understanding for cleaning. The four primary soiling mechanics were: (1) cementation by water-soluble salts, (2) deposition of organic materials, (3) surface tension, and (4) particle energetics. One of these—the cementation process—is represented in the progression in Fig. 24, and it is a critical process in many regions of the world having both high dust and humidity levels (such as heavy morning dews). Atmospheric dust contains a distribution of inorganic and organic particulates that contain some water soluble and insoluble salts. At high humidity, water-soluble dust particles on the surface form microscopic droplets of salt solutions that also retain any insoluble particles. When dried, the precipitated salt acts as a cement to anchor insoluble particles to the surface.

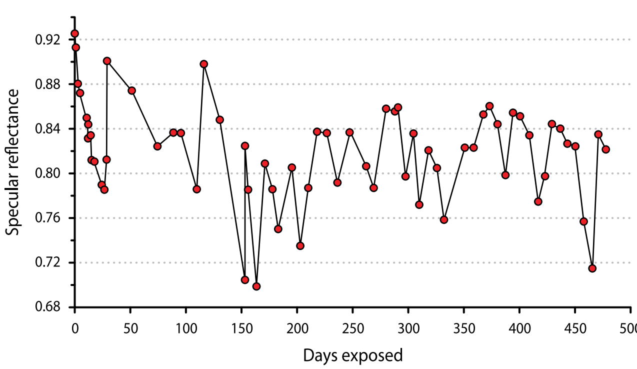


Fig. 23. Spectral reflectance of a second-surface silvered glass mirror exposed to atural weathering for 480 days. "Recovery" positive swings are due primarily to rain (Roth and Anaya [35]).

Ultrathin organic layers of organic deposition tend to coat the surface before other deposition occurs. This makes removing salt deposits more difficult, and in turn, leads to extended and/or more complex cleaning times and procedures. Surface tension forces can produce large forces and internal pressures within water droplets. "Particle energetics" encompasses particle–particle attractions, and these attractions increase with decreasing particle size in the below 10-μm regime. The attractive forces are van der Waals forces, and the Cuddihy experiments also show that wind speeds up to 150 m/s are *not* effective in removing these tightly held particles having diameters less than 10 μm.

Berg [15] provided an underpinning for dust mitigation studies, leveraging the knowledge and involvement in complementary experiments on dust accumulation-performance effects at Sandia National Laboratories. Berg investigated dust-deposition mechanics, materials, surfaces, and optical scattering to develop some logical cleaning strategies. He concluded that by understanding the mechanics of dust deposition, materials' surface properties, climatic conditions, and time development of the adhesion, only certain cleaning strategies would be effective. The strategies can be arranged according to approach (i.e., prevention or restoration) and the timescale over which they act. Table 6 summarizes these cleaning strategies for dust mitigation.

Berg designed early experiments to evaluate the preventative and restorative methods. But more importantly, he provided the foundations for dust mitigation studies that followed over the next 40 years—stressing that the scientific understanding of the problem was essential to any possible solution. Restorative and preventative approaches are both discussed in the following sections.

5.1. Restoration

Restoration involves post-soiling cleaning techniques to remove the dust and return the surface to as near its original

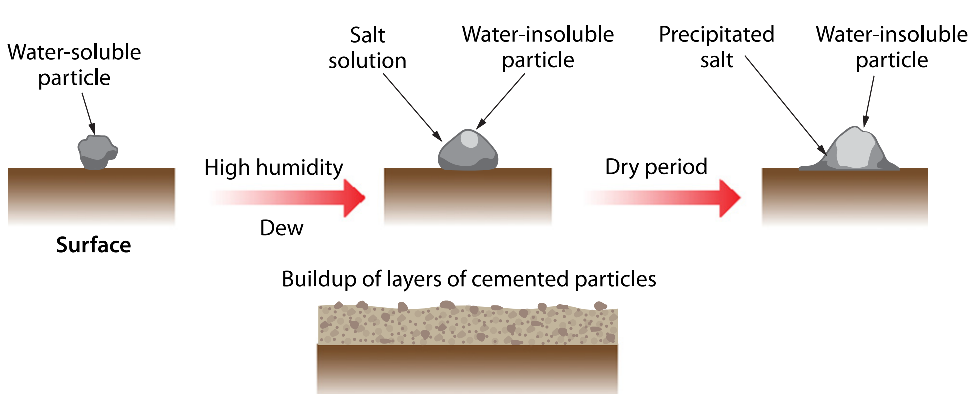


Fig. 24. Dust–moisture (water) cementation process (Cuddihy [39]).

Table 6
Summary based on cleaning strategies categorized by Berg [15] and supported by observations and experiments during that period [23,24,33].

Strategy	Description	Focus
Deterrence: Keep dirt from settling and adhering to the surfaces (***preventative***)	Uses noncontact, continuous techniques. Material and design intensive. Durability and lifetime concerns. No labor. Timescale: *Mid- to long-term*	New materials development; design and materials
Washing: Wash off the dirt with water or low surface energy detergent-type solutions before strong chemical or mechanical bonding can develop (***restorative***)	Involves frequent washing with detergent solutions, labor intensive, environmental impacts such as water usage, quality and disposal of wastewater. Labor intensive (possible automation). Time scale: *Short-term and immediate*	Primarily based on existing commercial products; operation and maintenance
Cleaning: Use chemical or mechanically active cleaning techniques capable of breaking the chemical and mechanical bonds (***restorative***)	Mechanical or chemical supplements to washings. Design intensive (i.e., automated high-pressure washers). Concerns about damage. Labor intensive (possible automation). Timescale: *Short-term and immediate*	Chemistry understanding and design; operation and maintenance
Surface modification: Modify the surface (treatments, coatings, films) so that strong bonding cannot develop (***preventative***)	Surface modifications or a substitute surface. Substitute surfaces can be permanent or temporary coatings such as surfactants that can be periodically restored. Materials transmission and interfaces important; durability and service lifetime. No labor. Timescale: *Long-term*	Physics and chemistry understanding; design and materials

condition as possible. Restoration certainly dominated the early ''resolution'' approaches of the dust problems. Much of this work during the 1970s and 1980s was directed to reflective surfaces because of the first large interests and investments in concentrated solar systems (primarily thermal) resulting from the oil crisis. These nascent research-level deployments and tests occurred in desert-type areas—rich in the required high direct-normal solar resource, but adversely affected with significant dust conditions. Thus, a major portion of the research conducted on mirrors and other reflectors necessitated developing techniques for keeping them clean. Sandia National Laboratories and the solar–thermal industry were among the first to develop mitigation techniques for the dust and soiling problems because of the early-adopter status of the United States. As the use of solar technology spread throughout the world, so have the financial and intellectual property investments in these mitigation schemes.

The first and most logical strategy is to mechanically remove the soiling by washing or wiping. This can involve using a cloth or other medium to wipe the surface. Or it may employ water or low surface-energy, detergent-based solutions to remove the soiling before any strong chemical or mechanical bonds can develop. These techniques, of course, can be extremely labor-intensive and require frequent and repeated procedures. If chemical agents are used, the chosen detergent solutions should be environmentally friendly. Furthermore, the solution-based processes can use significant amounts of water depending on the method used. The processes are potentially capable of some degree of automation (e.g., use of vehicles, robots, or mechanically integrated mechanisms). All these techniques add concerns about damage to the surfaces being cleaned.

Important to a cost-effective cleaning process is the determination of the periodicity of the cleaning. Excessive cleaning means more cost (labor) and more materials (e.g., water). Insufficient cleaning means unnecessary loss of power from the system. Installers and manufactures have invested some efforts and budgets in determining and optimizing these procedures. Typically, the cleaning is conducted during times when the system is disconnected from the load and/or during times that the balances of systems components are not operating (e.g., low light conditions, nighttime, etc.). If a fluid is used, it is best to have its temperature (within 10–15 °C is a rule of thumb) close to that of the surfaces to prevent excessive thermal shock. Abrasives are avoided—as well as fluids that act as degreasing agents. If the surfaces are to be cleaned under dry conditions, non-conductive materials (brushes, clothes, etc.) should be used. In all circumstances, it is best to consult the manufacturer to ensure that the process is compatible with either the module itself—and any coating that has been applied to it.

5.1.1. Washing (fluid-based)

5.1.1.1. Water. Water is a quite effective medium for surface cleaning. Nature has been a good friend of solar installations in much of the world, providing periodic washing of the surfaces via helpful weather patterns (e.g., rain and snow). However, for many regions, natural weather assistance has not been so widespread, and human intervention must be employed. Muller [23] and Sheratte [24] looked at using water exclusively as the cleaning agent, as well as other chemical solutions, evaluating various techniques and water qualities/sources. Conclusions of these works have stood as *modi operandi* since the time of his work that time: use of demineralized water was best, minimizing the deposit of other extrinsic materials carried by the solution; and, cleaning early in the morning when the mirrors are wet (from dew) is probably the best time because the dust can be easily rinsed from the coatings or surfaces "without" coating removal or damage. However, many investigators have noted over the years that the use of chemical agents can actually be quite beneficial in taking the solution cleaning to the next level—with active and added ability to remove particulates by considering the chemical bonding that might hold the soiling. An inherent benefit is that it would also require less water and less aggressive spraying/wiping, which could be a damage concern.

This McDonnell Douglas Astronautics Company/Sandia National Laboratories report on cleaning agents and techniques for concentrating solar collectors concluded that the removal of the rinsible soil was accomplished either by mild detergent rinse followed by soft water spray, or by application of 300 to 1000 psi spray of ordinary tap water containing a sheeting agent. It also concluded that each rinsing activity restored the reflector to the same specularity, 98% for glass and 92%–95% for acrylic, and further soiling and rinsing exercises always regenerate the same 2% specularity loss. The results also indicated that the glass reflector could be restored to 100% of its original reflectance at any time, either by scrubbing or spraying with detergent Triton Corporation of Houston, Texas, tested high-pressure sprays of tap water at 500, 1000, and 10,000 psi and recovered at least 95% of the original reflectance for each case [23,24,33]. The best technique today in this strategy is high-pressure sprays with commercial anionic detergents.

5.1.1.2. Cleaning solutions. Effective cleaning solutions typically employ chemicals (e.g., detergents) that possess the following attributes:

- able to reduce surface tension (surface energy)
- low-cost (in their solution volume)
- capable of being handled and mixed in automated equipment, and
- non-toxic, safe, and biodegradable.

Table 7
Summary of studies using forced air (blowing) with water mist and ultrasonic transducer assists [34].

Technique	Medium	Effectiveness	Observations and constraints
Vortex nozzle	Air	Good	Requires close proximity to surface (0.30″ or less for a typical 0.10″ nozzle); lifecycle costs of cleaning about the same as using solution (water plus detergents)
Converging nozzle	Air with water mist injection	Good to very good	Recovery of reflectance to 99% of original for mirrors. 10-cm separation from the surface for cleaning nozzle with 10 psig air. Water usage 2.14 mL/min (minimal water use)
Ultrasonic transducer with nozzle	Air with ultrasonic energy assist	Very good	Appreciably enhances the cleaning process of a mirror than with air blast alone (about 2% improvement). Transducer separation from mirror ~41 mm. Concluded to be best approach with improvement of transducer technology

Already cited, Berg's [15], Muller's [23], and Sheratte's [24] cleaning strategies (Table 6) provided the foundation on which other groups expanded and improved the approaches and materials. Schumacher et al. [34] published a preliminary design report dealing with new ideas for heliostat reflector cleaning systems. They evaluated a wide variety of commercial detergents for cleaning large-scale heliostat fields—e.g., Lime Brite, a descaler and home/commercial cleaner that is now available only in the United Kingdom; and Jet-X, an all purpose cleaner marketed for high-pressure spray washing of cars.[9] Most of these detergent-based solutions were able to recuperate up to 98% of the original surface reflectance. Among their observations are the following: (1) cloth wipes can leave streak marks or scratches on the mirror surfaces; and (2) high-pressure sprays proved to be a very effective method for cleaning large-scale mirrors or PV arrays (and capable of some degree of mobility automation). They provided a benchmark procedure that a 3-gallon per minute water spray at 300 psi (with various detergents) recovered up to 90% of the reflectance loss.

Roth and Pettit [36] and Sheratte [24] also built on the Berg work, integrating their soiling of solar mirror studies with identifying feasible cleaning techniques and cycles to maintain high reflectivity. They documented the mechanisms of natural soiling on mirror reflectance and glass transmission, concluding that the scattering effects and resultant losses on the concentrating (reflecting) surface were more significant for CSP than for PV flat-plate systems. Their long-term exposure experiments, with periods exceeding one year, showed large fluctuations in the reflectance due to weather conditions (e.g., rain, wind). The corresponding decrease in specular reflectance approached 15%. From their observations, Roth and Pettit proposed a set of cleaning-cycle experiments aimed at developing a cleaning procedure that was both effective (restorative) and cost effective. Mirrors were cleaned on 2-, 6-, and 12-day cycles, resulting in annual average reflectance losses of 0.85%, 18%, and 31%, respectively. Increased frequency of cleaning (i.e., more frequent than two days) were not any more effective. Through an orientation experiment, they found that 180° (inverted) and 90° were the angles that showed significant reduction in soiling (to minimize deposition during stowage). The effect of accumulated dust on specular reflectance was studied by careful laboratory-based hemispherical reflectance and wavelength-dependence measurements and determinations of beam-shape effects. The hemispherical reflectance test yielded no appreciable decrease in reflectance for specular reflectance losses up to 5%; energy lost from the specular component went into the diffuse scattering background, with no measurable loss due to absorption. There was a decrease in specular reflectance for all wavelengths as dust accumulation increased. Dust accumulation decreased the overall intensity of the reflected beam, but it did not significantly change the profile. A wind tunnel test was conducted using local dust at speeds of 10–30 mph to simulate accelerated deposition; reflectance losses were measured by laser optics. The study showed that reflectance losses decreased at higher wind speeds. It was thought that increased kinetic energy in the particles would "raise their energy above the effecting 'capture threshold' energy of the mirror and result in a drop in the effective 'sticking coefficient' of the small particles."

Planned, periodic washing in soiling-prone climates that have reasonable water resources is a practical approach. However, many areas are not so fortunate, and persistent dust and accumulation mandate regular cleaning-maintenance to maintain reliable system performance. Several approaches have been used and investigated ranging from "post-affliction treatment" (restorative measures such as washing, wiping, blowing, vibrating, or scraping) to "preventative medicine" (measures that include special surface preparation or additional instrumentation and use of innovative physics). A number of these approaches are detailed in this section, starting with some of the early approaches from the 1970s to 1990s and proceeding through some more recent promising technologies being pursued [16,18,23,24,33,37,139].

5.1.2. *Mechanical methods*

The first instinct is to mechanically remove the dust by wiping the surface with a cloth or some other soft medium—the simplest dry cleaning approach. Of course, this endangers the integrity of the surface, especially through scratching. Repeated wiping of abrasive sand on a reflective mirror or transmissive glass cover can destroy that surface completely, unless that surface has been hardened by some other means. One interesting cleaning procedure that has been used recently is one "stolen" from the street-corner entrepreneurs in Delhi, who use crumpled newspaper to clean windshields. This has been employed in some PV fields in India, with reported success. However, the concerns remain about damage with prolonged use of this technique. And the use on reflective surfaces is even more of a concern.

Alternate strategies use air flow ("forced air" directed at or across the surfaces) and vibrations. Schumacher et al. [34] presented preliminary designs and test results for devices using these two mechanisms for removing dust from the surface of solar collectors. In the air-flow approach, key parameters include velocity, duration, angle of incidence, and gas type. Two approaches were investigated to identify suitable cleaning methods. The first approach examined several air nozzles, including vortex-generating orifices (having combined rotational and translational motion to impart a "scrubbing action" to the air flow) and streamline nozzles that direct flow normal to the surface (with and without water flow). The second approach used a mechanical transducer—a simple mechanical plate with a piezoelectric transducer in the 21 kHz range—to impart ultrasonic energy through the air to the surface. Their results are summarized in Table 7.

[9] www.news.google.com/newspapers?nid=1917&dat=19670523&id=OPwtAAAAIBAJ&sjid=gYgFaaaaIBAj&pg=6848,4553376.

Their studies showed that the mechanisms using air flow (with and without water and ultrasonic energy assists) were able to recover significant amounts of the lost reflectance, proving that the technology is useful, although not as effective as washing. However, these methodologies are plausible for automated cleaners. They designed large-scale mobile vortex scrubber cleaning systems mounted on a truck body. This mobile truck cleaner was tested at Sandia National Laboratories and shown to have some effectiveness (Pettit et al. [21]), although the water system was far superior to the forced-air system alone.

There are a number of cleaning mechanisms and washes that are described on the internet (including some useful YouTube videos), which the reader can access through any search engine. These range from special solutions, to detailed methodologies and techniques, to automated solar panel cleaning systems. A number of these automated systems now recycle the solutions to minimize those environmental concerns.

5.2. Prevention

The "dust mitigation challenge" requires solutions that are tailored to both the intensity of the soiling process and the size/application of the solar system. At one end of the soiling spectrum, residential and small commercial systems may see negligible losses due to dust in parts of the world where rain and snow frequently occur. For dustier geographies or large utility-scale systems, dust accumulation can significantly reduce the capacity of the system. In these cases, cleaning or mitigating the dust problem becomes a necessary and cost-effective course of action. Skeptics sometimes write off any of the prevention approaches using coatings or active electronic elements because of initial added costs to the solar panels or heliostats. However, for large installations, cleaning can run into the range of multi-million dollars per year for fields that are now in the 200-MW size.

Glass has been the long-standing choice as the first protecting surface encountered by the incident solar radiation for PV modules and low-temperature solar–thermal collectors. On one hand, it is transparent, manufactured in large areas, and is a large component of our building industry. On the other hand, it is fragile, heavy, and not yet sufficiently inexpensive for solar applications, but it works. Lind and Hartman [38] had studied the natural degradation of soda-lime (float-zone) glass in desert climates to test if the material could withstand the environmental stresses of an outdoor environment for 40 years. The glass did show varying amounts of alteration in the surface morphology, chemical composition, refractive index, and spectral absorptance. However, these variations resulted in only minor changes in the optical properties, such as solar transmittance and specularity. Glass has proven to be the most durable transmissive component, serving the 30-year lifetimes demanded by PV modules. But it has been ineffective, with its normal surface characteristics, to avert dust accumulations.

Berg and others designed early experiments to examine several preventative methods:

- Prevention by *stowing* the array. To avoid dust accumulation during the night or during a dust storm, an array that is movable (e.g., a tracking CSP or CPV array) can be inverted or stowed during that time. One issue encountered is that if the dust storm approaches quickly or unexpectedly, the stowing process usually takes some time and can thus be ineffective.
- Prevention using *electrostatic repulsion* of the incident dust. The laboratory-scale investigation was conducted using a microscope slide coated with a conducting tin oxide (SnO_2) film and biased up to -1000 V to repel the positively charged dust particles. This approach was tested in a wind tunnel at Sandia with Arizona dust at speeds between 0 and 25 m/s. This experiment simulated 5–6 weeks of dust accumulation in 10 min. The test showed significantly less dust accumulation compared to non-treated glass.
- Prevention using *turbidity spoilers*. The specially designed and positioned aerodynamic spoilers induced a turbulent-flow boundary layer to promote "sweeping" of the dust from the surface. The preliminary results showed some slight improvement in dust accumulation. However, this innovative approach was reported to need more extensive development.
- Prevention by *vibrating* the surface. Vibrations are provided by special mechanical-electrical instrumentation for the device and activating it during high dust accumulation periods (e.g., dust storms) to prevent surface accumulation. Potentially, it can also be used to "free" particles from the surface after accumulation (Williams et al. [159]).

Table 8 provides a summary of various techniques investigated, with comments on their effectiveness and application criteria.

5.2.1. Surface modifications and coatings

The Holy Grail for the prevention community is to develop a coating that simply will not permit the dust to settle on the solar device surface. This coating should not only have this desirable property, but it must be durable and reliable while experiencing high temperatures, sandstorms, and higher than normal exposures to both ultraviolet (UV) and infrared—and it must be relatively inexpensive and easy to incorporate on the particular solar component [69,124,170,174,211]. Over the years, the interest in minimizing dust shifted toward developing alternative materials to replace the conventional glass/mirror or depositing coatings on the surface to change the tendency to accumulate dust—all without altering any of the optical properties. For PV, these investigations looked at special polymer covers such as

Table 8
Techniques investigated for preventing dust accumulation on solar surfaces (reflective and transmissive).

Technique	Comment
Stowing (inverting) for protection	May be ineffective because of time constants for stowing arrays; not applicable for fixed-axis arrays
Aerodynamic streamlining	Prevention of turbulent eddies and dead spots; special engineering required
Electrostatic biasing	Several hundreds to thousands of volts with normal electric field rejects particles; less effective with moisture (cementation)
Vibrating the surface	Accelerates the surface motion until particles can no longer move due to inertia; damage potential with long-term use of techniques (e.g., contacts)
Thermally induced air currents	Boundary type of phenomenon used on astronomical telescopes; reliability and cost are issues; potential for damage ("sand blasting")

polyethylene, polyvinyl chloride (PVC), and acrylics (Nahar and Gupta [69]; Mastekbayeva and Kumar [124] Miller and Kurtz [202], and Al-Helal and Alhamdan [174]). Even though some of these organic covers exhibit high initial transmittance, they actually tended to accumulate *more* dirt (due to high surface energies of the polymer surfaces), suffer abrasion damage, and degrade (often due to the high UV exposure) much quicker than glass.

What are the physical characteristics of an ideal surface that minimizes dust collection? Cuddihy [39] provides the earliest roadmap to the design and choice of coatings or surfaces to resist soiling. His menu of surface characteristics for low soiling includes surfaces that are:

1. Hard (less susceptible to embedding particles or being damaged by them)
2. Smooth (less likely to trap particles)
3. Hydrophobic (less attractive to ionic species, adsorption of solids, and retention of water)
4. Low-surface energy (lower chemical reactions)
5. Chemically clean (especially of materials classified as potentially "sticky")
6. Chemically clean of water soluble salts (which are likely to link with other soiling agents)

Cuddihy poses two primary techniques to achieve the desirable chemical characteristics—hydrophobicity and low surface energy—of low-soiling surfaces. The first technique for glass involves chemical coupling of fluorinated compounds to the glass surface, such as perfluorodecanoic acid chemically coupled with a silane coupling agent (e.g., Z-6020 by Dow Corning). Hexamethyl disilazane and reactive polysiloxanes (e.g., Dow Corning Emulsion 929, and Syl-Off 7044 and 7048 solvent coatings) can also be considered as chemically reactive materials.

The second technique involves chemical replacement on the surface of all Group I ions such as sodium and potassium with Group II and preferably Group III ions such as aluminum. It is known that Group I ions are generally hydrophilic, whereas Group II and generally Group III ions are hydrophobic. Furthermore, ion exchange with aluminum could significantly increase the surface hardness by the mechanism of ionic cross-linking to achieve a tougher, more weather-resistant surface. Plastic materials can also use ionic cross-linking to reduce soil retention. Acrylics are considered to be weather-durable plastics and candidates for aluminum ion cross-linking, which should increase the surface hardness and the hydrophobic characteristic [202, 213]. In general, hydrophilic formulations are designed to resist dust and soil accumulation and the sheeting of the water enables a more effective rinse—classified as high surface energy materials. These can be water-based formulations—making them more environmentally safe an allowing for application in the field. The hydrophobic formulations, on the other hand, cause high contact angles between the water droplets and the surface—and can then "roll" over the surface, removing soil during this kinetic movement (low surface energy classification). Both types of coatings are currently used for dust and soil mitigation—and engineering of these coatings is an area of active development. It should be added that high surface conductivity is an added surface feature providing and anti-static environment for preventing charged dust build-up.

Some mixed reports counter this set of dust-resistant surface characteristics, but these proposed surface properties have withstood the examinations over time. For example, Bonvin [91,93] tested various glass materials and surface treatments. For anti-soiling, his experiments concluded that the smooth glass typically outperformed other roughened glasses (in this case, textured glasses purposely used for light engineering to enhance PV module performance). However, some surface treatments that fit in the general categorization above—including Tefzel® films, hydrophobic coating Glasscad®, and Clear Shield®—did not show better resistance to dust deposition than the untreated glass.

He et al. [204] published a review of self-cleaning methods for solar cells. Park et al. [211] also examined the use of water-repellent coatings on solar cells to combat dust and moisture problems. Recently, some geometrically textured and nanotextured surfaces have been investigated because of initial indications that controlling the surface geometry can help mitigate the extent of soiling. Also, the development of superhydrophobic coatings has raised some expectations because of the moisture-dust problem, and these coatings are less binding for dust species and have lower surface energies. Superhydrophobic materials are typically organic-based, and they have accompanying concerns of lifetime with concerns about bond-breaking (causing darkening) under prolonged exposure to high levels of UV radiation [179]. Additionally, the durability has to be proved in conditions of high wind and sand causing erosion and their ability to withstand any cleaning procedures. Preliminary tests have been encouraging, and it is expected that this class of materials will continue to improve—especially with proposed nanostructured variations to enhance their physical and dust-mitigation characteristics.

5.2.2. Recent active prevention approaches

How do you proactively keep dirt from reaching, settling, and/or adhering to the surface? This strategy is to innovatively incorporate materials or system designs that use noncontact, continuous techniques that coincidentally require little or no labor for cleaning. The prime example of this strategy is a design using electrostatic repulsion [74,126,144,145,152,169,172,175,180,190,191,214]. This technique is sometimes referred to as "dry" cleaning because water and other solutions are not necessary in the process. This is particularly attractive in areas where water is a scarce commodity, such as in the arid regions of the MENA countries. It is also an "active technology" approach because it involves the special integration of electronic elements to accomplish the dust repulsion. There have been several studies conducted on this electrostatic repulsion approach, and preliminary results show that it is a plausible technique.

The first reports of using electric fields to prevent dust accumulation go back to the early 1970s—to Masuda and Aoyoma [4], who examined electrodynamics for particle control for applications ranging from environmental concerns to medical uses. Biryukov [98,99] developed some interesting and clever designs of this approach, such as a system involving dielectrophoretic forces to repel or attract dust particles from a surface. His initial proof-of-concept experiments were conducted using a wire electrode connected to a source of alternating current (AC) field and moved over the surface to be cleaned. Biryukov found that the "dry cleaning" was only effective for dust particles larger than

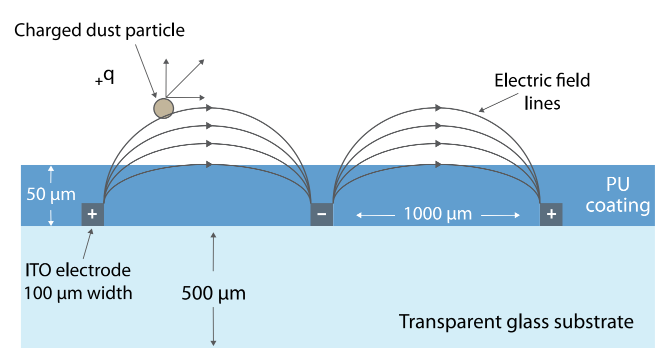


Fig. 25. Cross section of electrodynamic screen (EDS) (Mazumder et al. [183].

5 μm. The efficiency of dry cleaning decreased when the relative humidity was high, as well as when the dust was allowed time to settle (1 h) before cleaning, compared to immediate cleaning (1 min after dust deposition). The effectiveness was tested on a mirror surface with an original reflectance of 80%; dust was then deposited to reduce the reflectance to 76%, and finally, the reflectance was restored to 79.8% reflectance after "dry cleaning."

Transparent self-cleaning dust shields, based on electrodynamic screens (EDS), were patented by Mazumder et al. This group first became interested in this R&D because of the dust problems experienced during the Mars rover project. Mazumder et al. [152] reported EDS as a viable dust-mitigation system with preliminary designs requiring a high-voltage external power supply [157]—and they have expanded their interest [126, 151] to terrestrial dust issues. This EDS approach continues to be refined, and a cross section of the screen in shown in Fig. 25. Deposited transparent conductive electrodes, 50–100 μm wide and about 50 μm high, are embedded in a thin dielectric layer and separated by about 1000 μm. The exact electrode geometries and spacing depend on the material used and electrical characteristics. The dielectric is a polymer, and it is critical to the operation by providing a low surface energy for the process. The AC (4 to 20 Hz) 3-phase voltage applied between the electrodes is on the order of 3000 V. A traveling wave is generated by the electric field, with the 3-phase voltage energizing the electrodes. The charged particles are lifted off the surface by the vertical component of the electric field, and the traveling wave carries the dust particle to the edge of the electrodynamic screen (Fig. 25). The process is reported to be very efficient, with 95% or more of the dust removed. Mazumder has described a number of applications for this approach in addition to PV, including Fresnel lenses, thermal systems, and hybrid systems.

Recent advancements for self-cleaning solar panels with integrated electrodynamic screens (EDS) have been reported by Bock et al. [164]. The EDS comprises a series of alternating electrodes suspended in a transparent substrate. Three-phase high-voltage is applied to the alternating electrodes creating a traveling wave that "sweeps" the dust particles from one end of the surface to the other. This design not only removes dust from the surface, but can also operate without an external power source by harnessing the power necessary from the solar panels themselves. The configuration and wiring diagram is shown in Fig. 26.

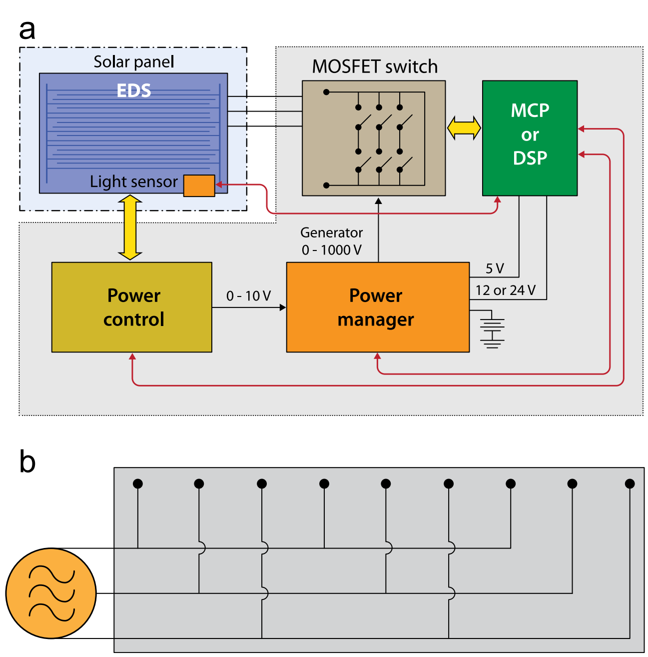


Fig. 26. EDS/PV array system: (a) Block diagram; (b) three-phase electrode configuration (Bock et al. [164]).

Biryukov et al. [182] further developed this electric-field approach with their new dielectrophoetic prototype device to remove the dust from the surface of a PV module. Efficiency of dust removal better than 90% was demonstrated. Further analysis of the transmission of glass samples, which were exposed to dust accumulation and cleaned "electrically," showed that the initial transmission of a fresh, clean glass plate could be restored almost completely by this method of dust removal. Finally, Clark et al. [176] reported an electrostatic tool for dust control ("SPARCLE"). This group focused on problems for lunar dust issues and other planetary exploration applications. SPARCLE is a compact device (<5 kg mass and using <5 W power) that could be fitted, for example, on a rover. It uses an electron beam to control the electrostatic potential of a surface. An oppositely charged plate then "induces" dust migration as a result of the electric field. This device is designed for space use, but it has some interesting implications for possible terrestrial applications.

These active approaches are innovative and offer alternatives for this next generation of dust-mitigation needs. However, some issues and questions have to be resolved. The first is the cost effectiveness associated with the added processing needed and any energy inputs. These costs have to be measured against the cost associated with the loss in performance and operation—and they may possibly more than justify the investment; this has to be determined. The second issue is the lack of effectiveness for the major problem associated with cementation—that is, the dust state being further compounded by interaction with moisture (e.g., heavy morning dews, excessive humidity). Other super-hydrophobic coatings may need to be included to guide off the moisture. Cost considerations are more complex. In any case, technology is needed, and the advances in nanotechnology and materials design hold great promise for eventual solutions to this important issue. [Note: Patents relating to the preventative methods are listed following the Reference and Literature Compilation section.]

6. Summary and observations

This review examines and summarizes the research, development, and challenges relating to the dust issues for solar collectors. The review has provided a comprehensive look at (1) performance and environmental effects, (2) dust issues for transmissive (i.e., glass and polymers) and reflective (mirror) surfaces for PV, CPV, and CSP, (3) dust particle analysis, and (4) various mitigation approaches and techniques, both preventative and restorative. Mani and Pillai [184] have provided a high-level but compelling "guide" to soiling conditions and mitigation for various regions of the world because of substantial variation in the weather, environmental, and temperature conditions. This paper has included a focus on the problems and conditions in the MENA region, primarily because of the growing interest and investments in solar technologies in this part of the world.

In summary, we provide four observations:

1. Dust and soiling remain problems in search of better solutions. This is especially valid for the desert-sand regions of the world, which ironically have some of the best solar conditions along with some of the "best" dust conditions! Compounding these are related environmental issues: a) Lack of natural cleaning by sufficient rain and other moisture that benefits the conditions in more temperate, tropical, and wet climates, and also, a profound shortage of indigenous water resources that could

provide an economical cleaning basis. And b), the little moisture that does occur can lead to even more severe soiling situations—those of cementation due to the combination of dew, very light rain, or humidity with dust.

2. Dust degrades the energy delivery of both PV and concentrating solar systems. Reduction in solar intensity reaching the solar converter has been evaluated and documented for the past five decades, and this reduction can typically be in the range of 20% to 50%, or more. This can lead to related reductions in performance (e.g., power output) from a PV system of 15% to 30% for moderate dust conditions. With cementation, losses to 100% have been encountered. Soiling is a more critical issue for reflective surfaces. Small losses in surface reflectivity of a mirror or heliostat result in major losses in CSP performance. In general, concentrating systems are more sensitive to dust accumulation and require more maintenance from the perspective of dust mitigation.
3. Much of the mitigation has focused on the restorative approach. Certainly, this approach dominated the developmental work in the 1970s through 1990s, with attention primarily on washing with water and water/detergent solutions. This included investigations of "automated" approaches for cleaning large systems (e.g., vehicle-mounted systems with forced water jets). Much of the body of work also looks at the effects of mechanical cleaning with air flows and air/water combinations from nozzles. The solutions-based systems are very effective, but depend heavily on the availability of quantities of water. Recommended cleaning schedules (see, e.g., [185]) depend on the geographic location and climatic zone.
4. Preventative approaches included both passive methods (which use coatings that prevent the attachment of the dust) and active methods (which actually repel the charged dust particles). All these methods are certainly "higher tech," and progress continues with substantial inputs from the materials science, chemistry, physics, and engineering research communities. In the coatings area, recent developments with (super-) hydrophilic (and superhydrophobic) materials have led to some promising results that are potentially effective for both dry and "wet" dust conditions.[10] However, the lifetime of these coating still needs to be validated. The inclusion of active layers to repel dust has grown out of interest and developments within the space industry. Several approaches have shown effectiveness and continue to be tested, evaluated, and analyzed for both technical and economic readiness. Of course, the recent advances with nanomaterials and technology and with the ability to pursue "materials by design" and the "materials genome" provide even further foundations and expectations that science will provide the solutions.

In the recent literature and from experiences in working in the field, a number of critical research and mitigation development needs have been identified to help abate the dust and soiling problems. Several significant recommendations are summarized below.

6.1. Metrology

- Methods to accurately measure *dust and soiling thicknesses* on exposed surfaces (and map this thickness parameter over the surface area).
- Methods to directly determine the *adhesive properties* (forces) of the dust to the surface.
- Determinations of the relationships between the ambient, airborne dust characteristics and that resulting component that deposits on the transmissive or the reflective surface. (Requires measurement of the ambient dust components.)

6.2. Modeling

More comprehensive consideration of complex mechanics to predict and understand and ensemble of dust parameters: Orientation dependence, surface property (roughness, chemistry) effects, installation geometries, turbulence due to wind and structures, orientations.

6.3. Materials science

- An encyclopedia on the chemistry and physical properties (e.g., composition, components, morphology, topography, mechanical) of dust from panels classified by geographical area and environmental conditions.
- Accurate studies of the (1) micro-level forces between the dust particles and surfaces, and (2) presence and effects of any binders (e.g., organic materials) on surface and inter-particle adhesion.
- R&D of possible *nanotechnology* approaches for materials discovery of new dust-resistant coatings and cleaning materials.

6.4. Mitigation techniques

- Effective dust "preventative coatings" and thin films for both dry-dust and moisture-dust conditions. Specifications include: (1) highly transparent to wavelengths of light required; (2) durable, with adequate service lifetimes; (3) non-toxic and Earth abundant; (4) able to be applied easily either during the panel/reflector preparation or in the field; and (5) inexpensive.
- Automated mechanical cleaning systems (air, water, solution) for large collector fields: (1) waterless or very water-conserving (recycling); (2) mobile operated or attached to the arrays; (3) using only clean fuels, if needed; and (4) durable, requiring minimal maintenance and operation labor.
- Sensors to detect the critical point for cleaning of surfaces (i.e., to initiate automatic cleaning techniques or to alert for problems with loss of dust coating effectiveness).

6.5. Forecasting

- Methodologies to predict sand/dust storms or anticipated high dust conditions. (Provide warning for stowing arrays or otherwise protecting them).
- Preparation and publication of dusk risk maps for major dust countries/areas [216].

6.6. Test facilities

The leading facility is at the Masdar Institute,[11] establishing this operation within the real world of "living the dust problem." Other test facilities either in operation or being planned include the following: the MNRE Solar Energy Center[12] in India, the Ministry of Science and

[10] http://www.lotusleafcoatings.com.

[11] http://www.masdar.ac.ae.

[12] http://www.mnre.gov.in/centers/about-sec-2/.

Technology[13] in Iraq, Sultan Qaboos University[14] in Oman, the Regional Center for Renewable Energy and Energy Efficiency[15] in Egypt, and KAUST[17] and K.A.CARE[16] in Saudi Arabia; SGS has constructed a "desert house" for dust evaluations in Germany.[18] If dust issues are to be resolved more rapidly, then there is a need to expand and coordinate these operations—perhaps through a global network—and to share data, results, and testing procedures.

6.7. Standards and certification

Currently, IEC 60068-2-68:1994, "Environmental testing – Part 2: Tests – Test L: Dust and sand,"—and its German version, DIN En 60068-2-68 LC2 1996—is the sole standard that specifies test methods to determine the effects of dust and sand suspended in air, on "electechnical" products. This is a general standard for electrical products that includes environmental testing conditions for electrical components and electrical equipment, specified sand testing conditions, test equipment, particle size distributions, artificial weathering tests, desert tests, safety measures in accordance with IEC Guide 104, dust tightness tests, and leak tests. With the increased number of solar deployments and potential in the desert areas, specific standards for PV and CSP need to be developed, including "dust" certification tests specific to these regions. These tests can vary significantly from very dry to humid, with very different dust issues for solar components, as discussed previously.

The R&D funding for cleaning methods has been modest; for coatings, funding has been minimal; and for the active prevention methods, even less. Soiling has now become "the" issue for many parts of the world—whether for solar systems installed at Masdar[19] in Abu Dhabi and Iraq, KAUST in Saudi Arabia, or major installations being planned for K.A.CARE[20] in Saudi Arabia and the Nehru Solar Mission for Rajasthan (Thar Desert) in India, or even moreso for future plans for DESERTEC projects[21] in the Sahara or the Gobi in China. Dust is an issue for solar, and we need to make the necessary R&D investments to ensure that it is not the showstopper for these important, clean-energy technologies.

NOTE: This review is intended to be a "living" document to be updated annually. The journal is inviting inputs from the readers as part of this effort. A special objective is to provide a status of improvements, new products, and new issues. More importantly, the literature compilation and listing of critical needs will be updated. We invite you to add to the publication list to ensure that it is as complete and useful as possible.

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[13] http://www.most.gov/iq.
[14] http://www.squ.edu.om.
[15] http://www.rcreee.org.
[17] http://www.kaust.edu.sa/.
[16] http://www.energy.gov.sa.
[18] http://www.sgs.com.
[19] http://www.masdar.ae.
[20] http://www.energy.gov.sa
[21] http://www.desertec.org/concept.

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